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Phenomenon Identification and Ranking Tables (PIRTs) for Loss-of-Coolant Accidents in Pressurized and Boiling Water Reactors Containing High Burnup Fuel

by

B. E. Boyack, C. A. Alexander, J. G. M. Andersen, J. A. Blaisdell, B. M. Dunn, D. Ebeling-Koning, T. Fuketa, G. Hache, L. E. Hochreiter, S. E. Jensen, S. Langenbuch, F. J. Moody, A. T. Motta, M. E. Nissley, K. Ohkawa, K. L. Peddicord, G. Potts, J. Rashid, R. J. Rohrer, J. S. Tulenko, K. Valtonen, N. Waeckel, and W. Wiesenack

October 11, 2000

EXECUTIVE SUMMARY

later

Acknowledgements

Several organizations, individuals, and resources were instrumental in supporting the PIRT panel efforts. Although the PIRT panel maintained an independent and separate perspective, the panel acknowledges the help received from the following individuals:

- Ralph Meyer of the NRC's Office of Nuclear Regulatory Research played a key role in planning and facilitating the panel's understanding of needs, as well as providing invaluable assistance in each of the panel's meetings.
- Harold Scott, Farouk Eltawila, and Frank Odar of the NRC's Office of Nuclear Regulatory Research helped create the programmatic elements which supported this effort.
- Several introductory and valuable presentations were made to the panel. Lawrence E. Hochreiter of the Pennsylvania State University, Mitchell E. Nissley of the Westinghouse Electric Company and Bert Dunn of Framatome Technologies prepared and presented information on the "PWR Loss of Coolant Accident (LOCA): Impact of High Burnup Fuel." Jens G. M. Anderson presented information on the "BWR LOCA." Mike C. Billone and Hee M. Chung presented a "Cladding Phenomena Overview."
- Gerald Potts and Arthur Motta, panel members, made significant contributions to Section 2.2, Description of Fuel and Cladding State. Arthur Motta, with assistance from panel member Joe Rashid prepared the original write-up for the PWR RIA report. Gerry Potts revised this information so that it was applicable to BWR fuel.
- The Electric Power Research Institute suggested industry participants for panel membership. These individuals represented a cross section of the nuclear power industry. The Advisory Committee on Reactor Safeguards suggested international participants for panel membership. With the exception of several university and private consultant members of the panel, the panel members were responsible for the expenses associated with their participation. The contributions of these institutions and individuals are gratefully acknowledged.

Finally we thank L. Rothrock of LANL Group TSA-10 for editing this report.

Acronyms

BWR	Boiling Water Reactor
DNB	Departure from Nucleate Boiling
EOL	End of Life
GDC	General Design Criterion
LOCA	Loss-of-Coolant Accident
LWR	Light-Water Reactor
MOX	Mixed Oxide Fuel
NRC	United States Nuclear Regulatory Commission
NSRR	Nuclear Safety Research Reactor
PCMI	Pellet-Cladding Mechanical Interaction
PIRT	Phenomena Identification and Ranking Table
PWR	Pressurized Water Reactor
RCS	Reactor Coolant System

Contents

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Abstract

In the United States, cladding embrittlement criteria and related evaluation models are used to address loss-of-coolant accidents. The embrittlement criteria are a peak cladding temperature of 1204 C (2200 F) and an equivalent oxidation of 17% of the cladding wall thickness. Evaluation models address ballooning, rupture, flow blockage, and oxidation kinetics. The other consists of several threshold values that are used to indicate cladding failure. In the 1970s, high burnup was thought to occur around 40 GWd/t (average for the peak rod). Data out to that burnup had been included in databases for criteria, codes, and regulatory decisions. It was believed that some extrapolation in burnup could be made and fuel burnups in licensed reactors up to 62 GWd/t (average for the peak rod) were permitted. By the mid 1980s, however, unique changes in pellet microstructure had been observed from vendor and international data at higher burnups along with increases in the rate of cladding corrosion. It thus became clear that other phenomena were occurring at high burnups and that continued extrapolation of transient data from the low-burnup database was not appropriate. The U.S. Nuclear Regulatory Commission (NRC) is addressing these issues. It is performing research with respect to high burnup fuel to acquire and develop the requisite understanding of the performance of high burnup fuel under accident conditions. It is also conducting research to determine if current embrittlement criteria and evaluation models are adequate for high-burnup fuel or if modifications are needed. To support these efforts, The NRC has commissioned the formation of a Phenomena Identification and Ranking Table (PIRT) panel to identify and rank the phenomena occurring during selected transient and accident scenarios in both pressurized water reactors and boiling water reactors containing high burnup fuel. Because the PIRT identifies and ranks phenomena for importance, existing experimental data and planned experiments, computational tools (codes), and code-calculated results can be screened to determine applicability and adequacy using the PIRT results. This PIRT identifies and ranks phenomena for loss-of-coolant accidents in both pressurized and boiling water reactors. A spectrum of break sizes have been considered in preparing the PIRT.

1. INTRODUCTION

The United States (US) Nuclear Regulatory Commission (NRC) has commissioned the formation of a Phenomena Identification and Ranking Table (PIRT) panel to identify and rank the phenomena occurring following selected transient and accident scenarios in pressurized water reactors (PWR) and boiling water reactors (BWR) containing high burnup fuel. The panel will prepare PIRTs for the following three scenarios: (1) PWR reactivity initiated accident (RIA), (2) BWR instability power oscillations arising in an anticipated transient without scram (ATWS), and (3) PWR and BWR loss-of-coolant accidents (LOCA). The remainder of this report collects and documents the findings of the High Burnup Fuel PIRT panel for the PWR and BWR LOCA. Additional reports will be issued for the other two scenarios.

The report is organized into five sections and contains six supporting appendices. Section 1, Introduction, summarizes the issues associated with high burnup fuel, provides an overview of the PIRT process, identifies the members of High Burnup Fuel PIRT panel, and identifies the objectives of the PIRT effort. Section 2, PIRT Preliminaries, describes elements of the PIRT process, as applied to the high burnup fuel issue, which lay the foundation for the identification and ranking of phenomena. Section 3, PWR and BWR LOCA PIRTs, contains the PIRT tables. Section 4, Databases, describes the experimental and analytical databases used by the panel during the development of the BWR ATWS PIRT. Section 5, Additional Panel Insights, documents PIRT panel insights in two areas, technical and procedural. The phenomena descriptions and rationales for importance ranking, applicability, and uncertainty are presented in Appendices A through D. Appendix A contains the phenomena descriptions and rationales for Category A, Plant Transient Analysis. Appendix B contains the phenomena descriptions and ranking rationales for Category B, Integral Testing. Appendix C contains the phenomena descriptions and ranking rationales for Category C, Transient Fuel Rod Analysis. Appendix D contains the phenomena descriptions and ranking rationales for Category D, Separate Effect Testing. Appendix E contains descriptions of the applicable experimental databases. Brief experience summaries for each panel member are provided in Appendix F.

1.1. Background

The NRC's research program is focusing on events that have significant risk. Because risk derives from both probability and consequence, data about each contributor is needed. The radiological consequence of an accident in a nuclear power plant is most directly associated with fuel melting. Therefore, the NRC is examining design basis accidents that involve fuel damage criteria, the purpose of the criteria being to prevent the progression of an accident into a severe accident with serious radiological consequences.

The NRC is screening events by considering two classes. The first is the class of events in which too much power is generated and the second is the class of events in which there is insufficient coolant.

In earlier PIRT efforts, a PWR reactivity-related accident and a BWR accident with instability power oscillations arising during an anticipated transient without scram were considered.[1-1, 1-2] These two accidents were representative of a class of events in which too much power is generated. In this report, PWR and BWR LOCAs are considered. The PWR and BWR LOCAs are representative of the class of events in which there is insufficient coolant. A spectrum of break sizes has been considered for each reactor type.

In the United States, regulatory criteria have been developed for ensuring the the Emergency Core Cooling System (ECCS) can adequately cool the core following a LOCA. Five specific design acceptance criteria have been specified for the ECCS.[1-3] The five criteria are: (1) the calculated maximum peak cladding temperature shall not exceed 2200 °F, (2) the calculated local oxidation of the cladding shall nowhere exceed 0.17 times the local cladding thickness before oxidation, (3) the total amount of hydrogen generated shall not exceed 0.01 (1%) of the total amount which could be generated from all the cladding which surrounds the fuel, (4) calculated changes in core geometry shall be such that the core remains amenable to cooling, and (5) after any calculated successful operation of the ECCS, the calculated core temperature shall be maintained as an acceptably low value and decay heat shall be removed for an extended period of time as required by the long-lived radioactivity remaining in the core.

In the 1970s when the regulatory criteria and related analytical methods were being established, high burnup was thought to occur above 40 GWd/t (average for the peak rod). Data out to that burnup had been included in databases for criteria, codes, and regulatory decisions, and it was believed that some extrapolation in burnup could be made. Fuel burnups in licensed reactors up to 62 GWd/t (average for the peak rod) were permitted. By the mid 1980s, however, unique changes in pellet microstructure had been observed from both vendor and international data at higher burnups along with increases in the rate of cladding corrosion (breakaway oxidation). It thus became clear that additional phenomena were occurring at high burnups and that continued extrapolation of transient data from the low-burnup database was not appropriate.

By the 1990s, large amounts of oxidation (corrosion) were accumulating on Zircaloy fuel that was being pushed to higher burnups. In the U.S. a defacto limit of 100 microns of oxide thickness was implemented. At this level, however, as much as 14% of the cladding wall thickness has been oxidized and the obvious question was raised about the effect of pre-accident corrosion on the allowable oxidation during the accident. The NRC, as an interim measure, interpreted the allowable 17% total oxidation to include pre-accident corrosion thus sharply limiting the amount of additional oxidation that could be tolerated during such an accident.

[To address the question of total oxidation and the adequacy of related evaluation models for high-burnup fuel, the NRC established a testing program at Argonne National Laboratory with EPRI cooperation. The NRC also expanded its colaboration with researchers in France, Japan, and Russia to include information exchanges on LOCA-related research.

Although the test and analytical programs underway provide valuable data for an interim assessment, these programs have also provided enough understanding of the related phenomena to know that the current database has substantial limitations. To address these uncertainties in a cost-effective manner, the NRC will continue to participate in experimental programs through international agreements as well as code-related efforts within the U. S.

The NRC has embarked on efforts to address two important needs. The first need is to identify the research to be done by the NRC and industry with respect to high burnup fuel to acquire and develop the requisite understanding of the performance of high burnup fuel under accident conditions. The second need, as previously stated, is to develop revised regulatory limits for fuel damage if they are needed. The PIRT documented in this report is a tool that will be used by the NRC in addressing these two needs. The PIRT presented in this report can be visualized as a lens through which existing experimental data and planned experiments can be examined. Because the PIRT both identifies and ranks phenomena for importance, existing experimental data and planned experiments can be viewed through the PIRT lens to determine adequacy. Likewise, both computational tools (codes) and code-calculated results can be viewed through the PIRT lens to determine applicability and adequacy.

The role of the PIRT in addressing the needs identified above is illustrated in Fig. 1-1. There are many specific questions that must be answered while addressing the NRC's needs. As answers are collected and issues resolved, the knowledge and understanding required to satisfy NRC's needs will be obtained. It must be noted that the PIRT will be just one of several tools and approaches used to ensure the requisite knowledge is acquired and understood.

1.2. PIRT Panel Membership

The panel members were selected after considering background related to plant type, accident scenarios, and technical expertise, e.g., materials science, reactor kinetics and physics, thermal-hydraulics, etc. It was decided that one PIRT panel would be formed rather than creating a separate PIRT panel for each plant type and scenario. This approach minimizes the startup time for a new PIRT panel and permits the ongoing panel members to utilize the insights gained in the initial PIRT efforts for subsequent PIRT efforts. Representatives of each US reactor vendor, utilities, and members of the international community were asked to participate.

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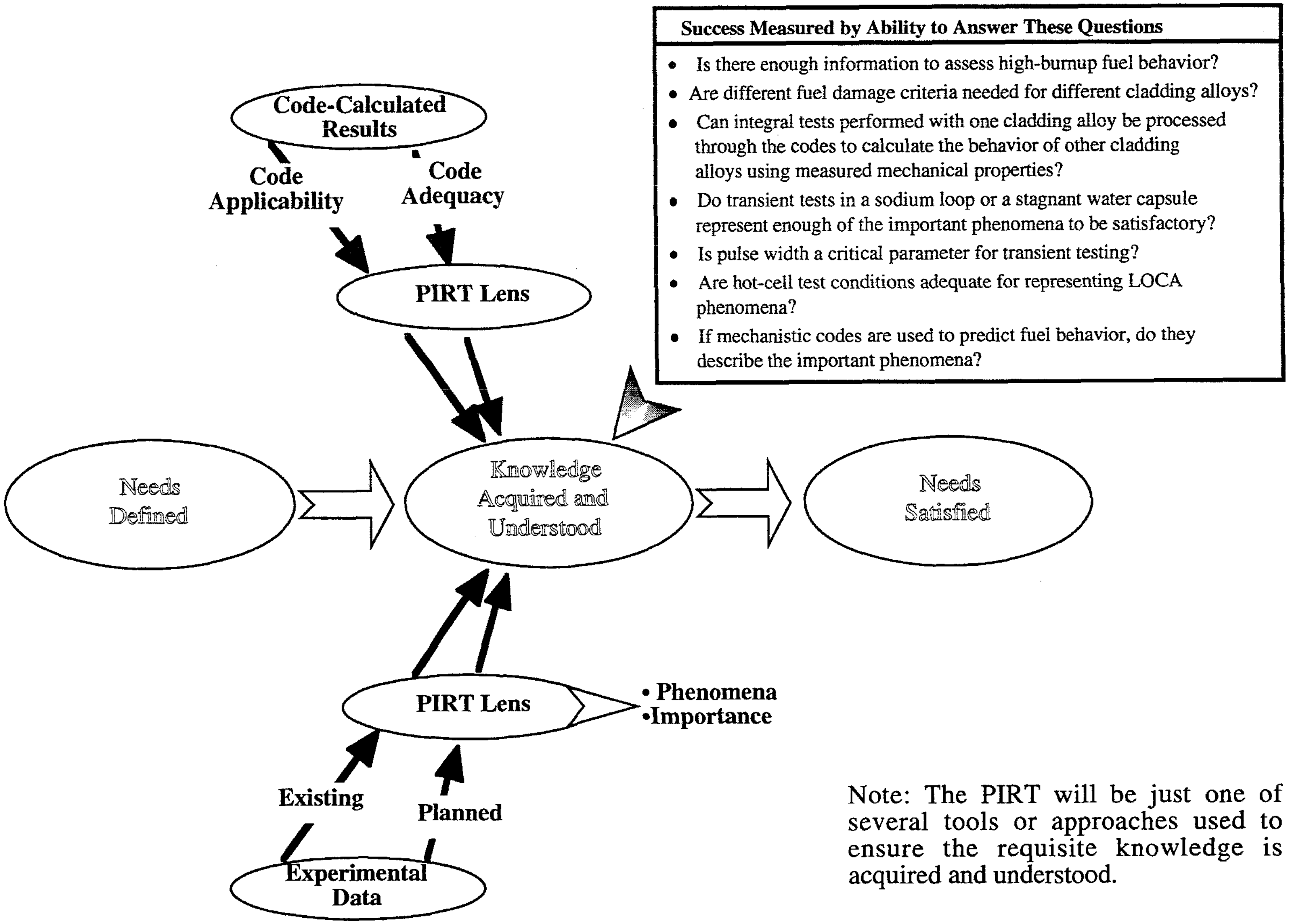

Note: The PIRT will be just one of several tools or approaches used to ensure the requisite knowledge is acquired and understood.

Fig. 1-1. Use of PIRTs to address NRC needs.

The High Burnup Fuel panel members participation in the PWR and BWR LOCA PIRT are:

- Carl A. Alexander, Battelle Memorial Institute
- Jens G. M. Andersen, Global Nuclear Fuel, Inc.
- John A. Blaisdell, Westinghouse Electric Company (Combustion Engineering Nuclear Power LLC).
- Burt Dunn, Framatome Technologies, Inc.
- Derek B. Ebeling-Koning, Westinghouse Electric Company (Combustion Engineering Nuclear Power LLC).
- Toyoshi Fuketa, Japan Atomic Energy Research Institute
- Georges Hache, Institute for Protection and Nuclear Safety
- Lawrence Hochreiter, The Pennsylvania State University
- S. E. "Gene" Jensen, Siemens Power Corporation
- Siegfried Langenbuch, Gesellschaft fuer Anlagen- und Reaktorsicherheit (GRS) mbH
- Fred Moody, Consultant
- Authur Motta, The Pennsylvania State UniversityMitchell E. Nissley, Westinghouse Electric Company
- Katsuhiro Ohkawa, Westinghouse Electric Company
- Kenneth Peddicord, Texas A&M University
- Gerald Potts, Global Nuclear Fuel, Inc.
- Joe Rashid, Anatech Corporation
- Richard Rohrer, Nuclear Management Company
- James S. Tulenko, University of Florida
- Keijo Valtonen, Finnish Center Radiation and Nuclear Safety
- Nicolas Waeckel, Electric Power Research Institute
- Wolfgang Wiesenack, Halden Reactor Project

The facilitator for the High Burnup Fuel PIRT panel is Brent E. Boyack, Los Alamos National Laboratory. Brief experience summaries for each panel member and the panel facilitator are presented at the end of this volume in Appendix F.

1.3. PIRT Overview

The PIRT process has evolved from its initial development and application[1-4, 1-5, 1-6] to its description as a generalized process.[1-7] A PIRT can be used to support several important decision-making processes. For example, the information can be used to support either the definition of requirements for related experiments and analytical tools or the adequacy and applicability of existing experiments and analytical tools.

This is important because it is neither cost effective or required to assess each feature of an experiment or analytical tool in a uniform fashion. The PIRT methodology brings into focus those phenomena that dominate, while identifying all plausible effects to demonstrate completeness.

A simplified description of the PIRT process, as applied to the development of the PWR and BWR LOCA PIRT for high burnup fuel, is illustrated in Fig. 1-2 and described below.

Step 1 is to define the issue that is driving the need, e.g., licensing, operational, or programmatic. The definition may evolve as a hierarchy starting with federal regulations and descending to a consideration of key physical processes.

Step 2 is to define the specific objectives of the PIRT. The PIRT objectives are usually specified by the sponsoring agency. The PIRT objectives should include a description of the final products to be prepared.

Step 3 is to define the hardware and equipment scenario for which the PIRT is to be prepared. Generally, a specific hardware configuration and specific scenario are specified. Experience gained from previous PIRT efforts indicates that any consideration of multiple hardware configurations or scenarios impedes PIRT development. After the baseline PIRT is completed for the specified hardware and scenario, the applicability of the PIRT to related hardware configurations and scenarios can be assessed as illustrated in Fig. 1-2.

Step 4 is to define the primary evaluation criterion. The primary evaluation criterion is the key figure of merit used to judge the relative importance of each phenomenon. It must, therefore, be identified before proceeding with the ranking portion of the PIRT effort. It is extremely important that all PIRT panel members come to a common and clear understanding of the primary evaluation criterion and how it will be used in the ranking effort. For the PWR and BWR LOCA PIRT effort, the primary evaluation criterion is derived from regulatory requirements.

Step 5 is to compile and review the contents of a database that captures the relevant experimental and analytical knowledge relative to the physical processes and hardware for which the PIRT is being developed. Each panel member should review and become familiar with the information in the database.

Step 6 is to identify all plausible phenomena. A primary objective of this step is completeness. In addition to preparing the list of phenomena, precise definitions of each phenomenon should be developed and made available to the PIRT panel to ensure that panel members have a common understanding of each phenomenon.

Step 7 is to develop the importance ranking and associated rationale for each phenomenon. Importance is ranked relative to the primary evaluation criterion adopted in Step 5. For PIRT panels having 6-8 members, importance discussions usually lead to a single importance rank for a given phenomenon. For PIRT panels having more members such as the present case (see Section 1.2), it has been determined that voting on importance is more efficient. With a large panel, individual members may be experts in some of the phenomena identified but be less familiar with others. To deal with this reality, panel members are informed that they need vote only if they feel they have sufficient understanding of the importance of the phenomena. Panel members must take care to focus solely on importance relative the primary evaluation criterion when voting. The degree of knowledge or understanding of the phenomenon is handled separately in the next step.

Step 8 is to assess the level of knowledge, or uncertainty, regarding each phenomenon. This is new step in the evolving PIRT process. It was not included, for example, in a recent generalized description of the PIRT process.[1-7] By explicitly addressing uncertainty, an observed defect of earlier PIRT efforts has been addressed, namely, the tendency of PIRT panel members to assign high importance to a phenomenon for which it is concluded that there is significantly less than full knowledge and understanding.

Step 9 is to document the PIRT results. The primary objective of this step is to provide sufficient coverage and depth that a knowledgeable reader can understand what was done (process) and the outcomes (results). The essential results to be documented are the phenomena considered and their associated definitions, the importance of each phenomena and associated rationale for the judgement of importance, the level of knowledge or uncertainty regarding each phenomenon and associated rationale, and the results and rationales for any assessments of extended applicability for the baseline PIRT. Other information may be included as determined by the panel or requested by the sponsor.

As presented in Fig. 1-2, the PIRT process proceeds from start to end without iteration. In reality, however, the option to revisit any step is available and is sometimes used in the PIRT development process.

1.4. PIRT Objectives

The PIRT panel has been organized to develop a PIRT for a PWR or a BWR containing high burnup fuel and experiencing a loss-of-coolant accident. The PIRT is to be developed and documented so that it can be used to help guide future NRC-sponsored analytical, experimental, and modeling efforts conducted as part of its program to assess and revise if necessary the LOCA embrittlement criteria and related evaluation models.

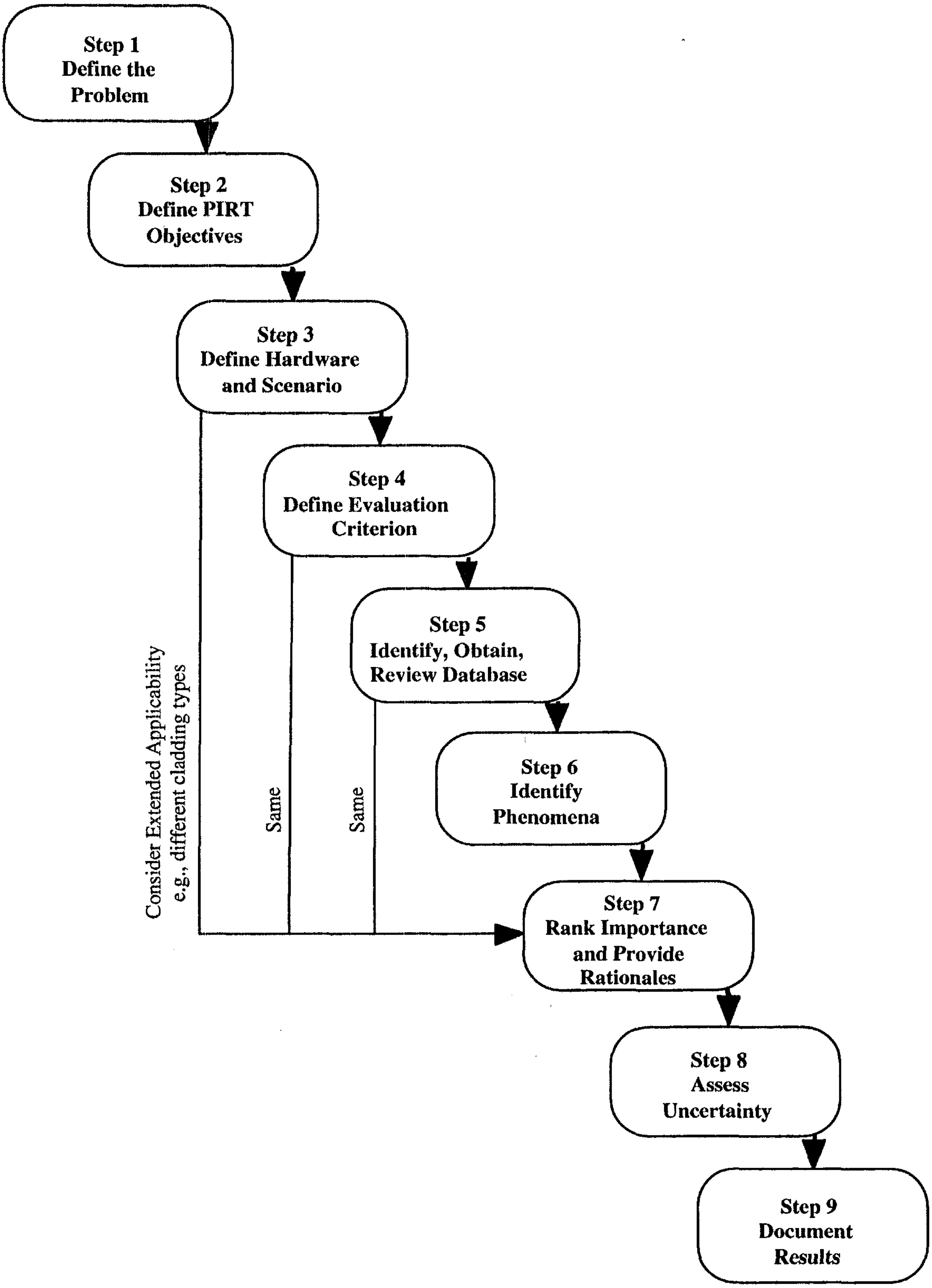

Fig. 1-2. Illustration of PWR and BWR LOCA PIRT process.

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2. PIRT PRELIMINARIES

Several important preliminary steps must be completed in advance of the identification and ranking efforts of the PIRT process. The PIRT objective was defined and documented in Section 1.4. During the PIRT development process, each PIRT is developed for a specific plant and scenario because both the occurrence of phenomena and processes and the importance of phenomena and processes are plant and scenario specific. The plant and fuel designs selected for this PWR and BWR LOCA PIRT development are discussed in Section 2.1. Descriptions of the selected fuel types for this PIRT and its state at high burnup prior to an oscillation event are described in Section 2.2. The accident scenarios selected for the LOCA PIRT are discussed in Section 2.3. Fuel and cladding behavior during the event are described in Section 2.3.2. In a departure from the standard PIRT process, the PIRT panel grouped the phenomena under consideration into categories associated with code and experimental activities. The four categories defined for the PIRT are described in Section 2.4. The panel broadened the definition of the term "phenomena," as it appears in the PIRT acronym, to include phenomena, processes, conditions, and properties. This approach was taken to facilitate the panel's involvement in both the development of the PIRT and consideration of the PIRT's application to (a) modifications that might be needed in plant transient codes for licensing analysis, (b) experimental derivation of a quantitative fuel enthalpy criterion, and (c) development of transient fuel rod codes that might be introduced into regulatory assessment. The PIRT panel performed the ranking effort relative to a primary evaluation criterion. Therefore, it is important that this criterion be explicitly defined, as is done in Section 2.4. The categories of phenomena are discussed in Section 2.5. The categories of phenomena are discussed in Section 2.5. The phenomena ranking scale is described in Section 2.6, with an accompanying discussion of the voting process and voting rationale. Panel efforts in the areas of extended PIRT applicability and uncertainty evaluation are provided in Sections 2.7 and 2.8, respectively.

2.1. Selected Plant and Fuel

The LOCA PIRT has been developed for both PWR and BWR reactors. However, PIRT development becomes very difficult if the panel considers more than a single reactor or reactor type when developing the baseline LOCA PIRT. For the LOCA PIRT, the panel decided to develop the baseline PIRT for a PWR plant and then evaluate changes to the baseline PWR LOCA PIRT as part of evaluating "Extended Applicability" for the PIRT. These results are reported in the PIRT tables presented in Section 3.

2.1.1. PWR Plant

No specific PWR plant was selected for the PWR element of the LOCA PIRT. However, the primary LOCA overview information presented to the PIRT panel was for a Westinghouse 4-loop PWR. The coolant piping is arranged in a 4x4 configuration consisting of four hot legs, four steam generators, four coolant pumps, and four cold legs.

The primary coolant system of a Westinghouse PWR consists of a multi-loop arrangement arrayed around the reactor vessel as shown in Fig. 2-1[2-1]. In a typical four-loop configuration, each loop has a vertically oriented steam generator and a coolant pump. The coolant flows through the steam generator within an array of U-tubes that connect inlet and outlet plena located in the bottom of the steam generator. The system's single pressurizer is connected to the hot leg of one of the loops.

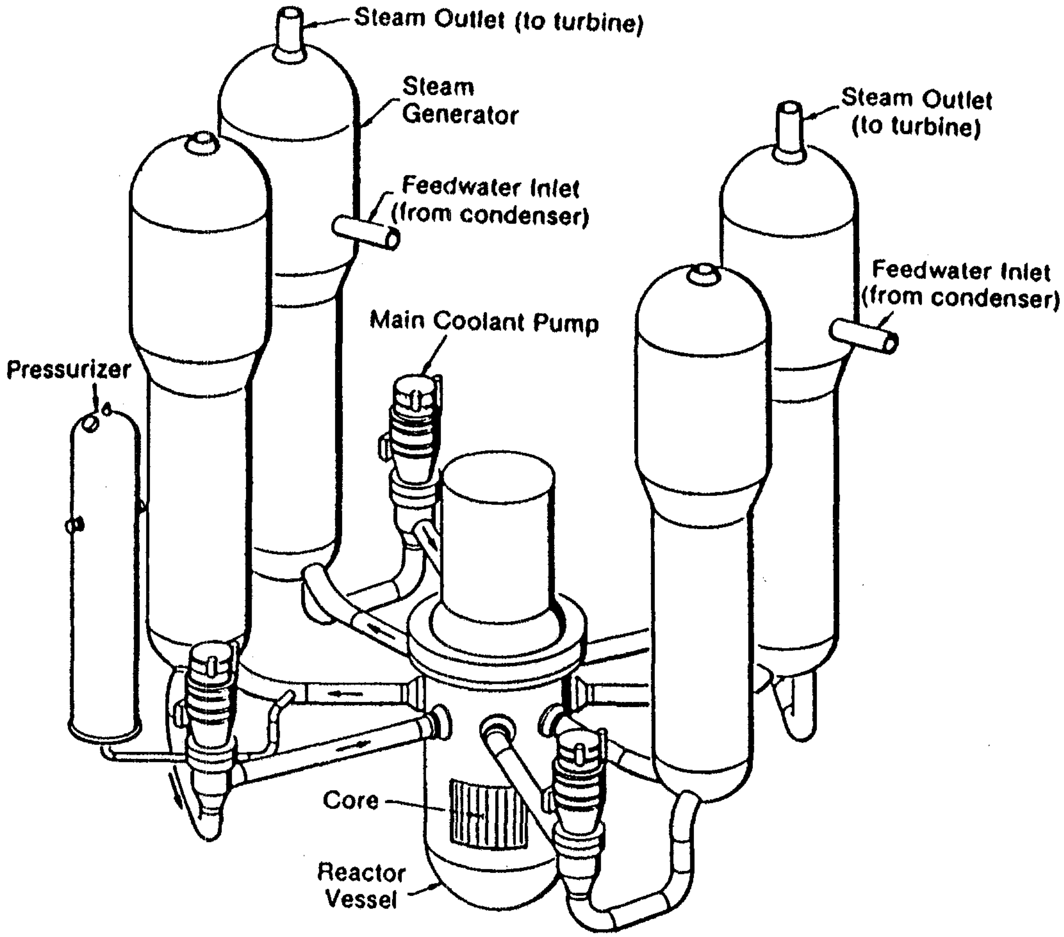

Fig. 2-1. PWR primary system arrangement.

During normal operation, the inlet nozzles (cold legs) communicate with an annulus formed between the inside of the reactor vessel and the outside of the core support barrel. Coolant entering this annulus flows downward into the inlet plenum formed by the lower head of the reactor vessel. Here it turns upward and flows through the core into the upper plenum which communicates with the reactor vessel outlet nozzles (hot legs).

With the exception of beginning of life plant startup, a reactor core usually contains a mixture of new fuel assemblies, i.e., newly fabricated fuel assemblies being introduced into the reactor core for the first time, and assemblies that have resided in the core for various lengths of time. During its time of residence in the core, the fuel undergoes burnup, that is, the nuclear-reactor fuel is consumed. Thus, burnup is a measure of nuclear reactor fuel consumption, expressed as the amount of energy produced per unit weight of fuel. For the present PIRT, the fuel with the highest burnup is assumed to have a burnup of 62 gigawatt days/metric ton (GWd/t). A description of high burnup fuel is provided in the following section.

Although a specific plant and fuel have been selected, the panel recognizes the desirability of extending the applicability of the PIRT for the specified plant and fuel. Accordingly, the panel elected to perform a preliminary screening of the phenomena identified for the selected plant, fuel and cladding to other plants [Westinghouse (W), Babcock and Wilcox (B&W), and Combustion Engineering (CE)], fuel types [mixed-oxide (MOX) fuel utilizing fissile plutonium], cladding types introducing niobium (Nb) or having reduced tin (Sn) content [ZIRLO, Duplex, M5, etc.], and burnup to 75 GWd/t.

2.1.2. BWR Plant

As described in Section 2.1, the panel decided to develop the baseline PIRT for a PWR plant and then evaluate changes to the baseline PWR LOCA PIRT as part of evaluating "Extended Applicability" for the PIRT.

To prepare for evaluating the extended applicability of the PIRT, the panel received overview information regarding the response of BWR plants to a spectrum of LOCAs. Details were first provided for the response of a generic BWR/6 plant to a large-break LOCA, after which additional information was provided about the response of a generic BWR/4 and BWR/2 plant to the same event.

The steam and recirculation water flow paths in a BWR are shown in Fig. 2-2[2-1]. The steam-water mixture first enters steam separators after exiting the core. After subsequent passage through steam dryers located in the upper portion of the reactor vessel, the steam flows directly to the feedwater system. The water, which is separated from the steam, flows downward in the periphery of the reactor vessel and mixes with the incoming main feed flow from the turbine. This combined flow stream is pumped into the lower plenum through jet pumps mounted around the inside periphery of the reactor vessel. The jet pumps are driven by flow from recirculation pumps located in relatively small-diameter external recirculation loops, which draw flow from the plenum just above the jet pump discharge location. The fuel is uranium dioxide (UO_2) and the cladding is zircaloy-2 with a zirconium-based inner liner. Each fuel assembly has several fuel rods with a burnable poison, gadolina (Gd_2O_3) mixed in solid solution with UO_2.

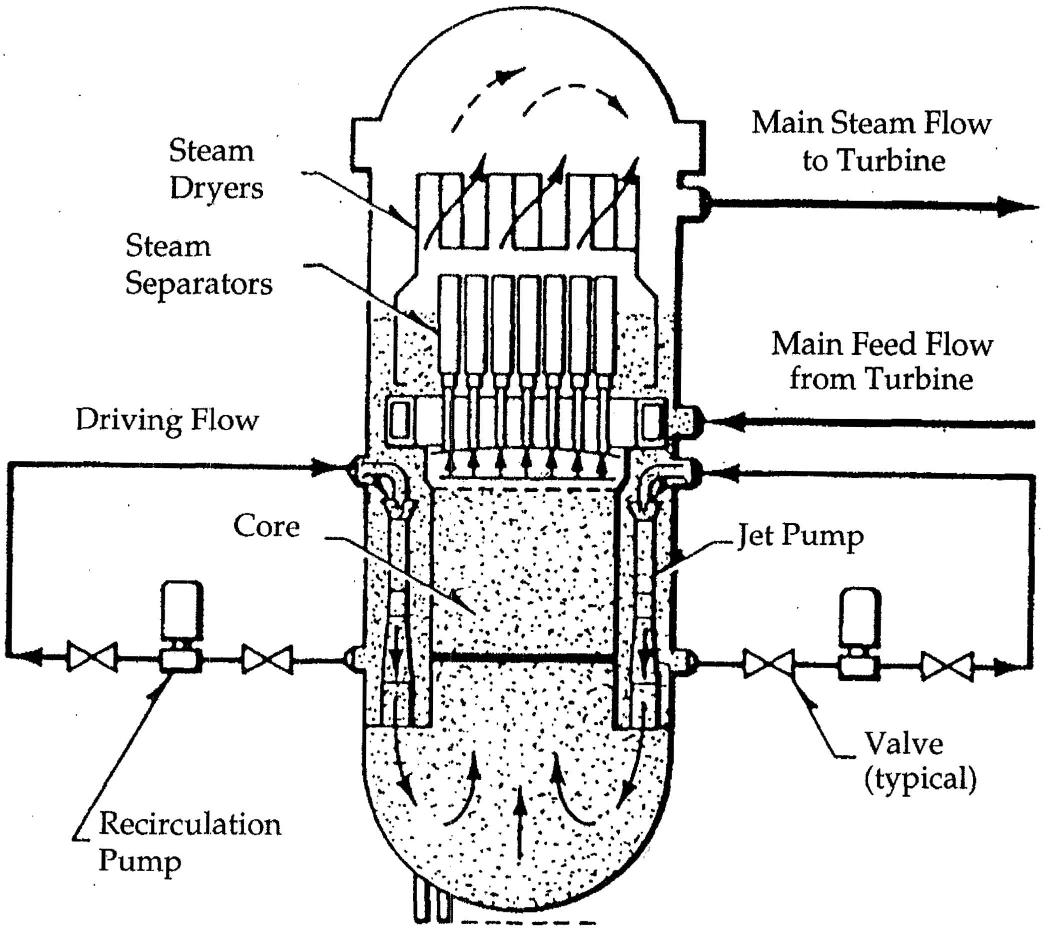

Fig. 2-2. Steam and recirculation water flow paths in the BWR.

With the exception of beginning of life plant startup, a reactor core usually contains a mixture of new fuel assemblies, i.e., newly fabricated fuel assemblies being introduced into the reactor core for the first time, and assemblies that have resided in the core for various lengths of time. During its time of residence in the core, the fuel undergoes burnup, that is, the nuclear-reactor fuel is consumed. Thus, burnup is a measure of nuclear-reactor fuel consumption, expressed as the amount of energy produced per unit weight of fuel. For the present PIRT, the fuel with the highest burnup is assumed to have a burnup of 62 gigawatt days/metric ton (GWd/t). A description of high burnup fuel is provided in the following section.

Although a specific plant and fuel have been selected, the panel recognizes the desirability of extending the applicability of the PIRT for the specified plant and fuel.

Accordingly, the panel elected to perform a preliminary screening of the phenomena identified for the selected plant, fuel and cladding to other plants [BWR/2-/6], fuel types [mixed-oxide (MOX) fuel utilizing fissile plutonium], cladding types introducing niobium (Nb) or having reduced tin (Sn) content [ZIRLO, Duplex, M5, etc.], and burnup to 75 GWd/t.

2.2. Description of Fuel and Cladding State at High Burnup

Related PIRTs have been prepared for a PWR rod ejection accident[2-2] and for instability power oscillations arising during an anticipated transient without scram in BWRs.[2-3] In each case, a description of the anticipated fuel and cladding state just prior to the event was prepared. These descriptions are also applicable to the PWR and BWR LOCA events and are repeated in this document. The description of PWR fuel and cladding at high burnup is provided in Appendix G; the description of BWR fuel is presented in Appendix H.

2.3. Accident Scenario

Brief descriptions of three LOCA scenarios are presented below. The scenarios are for the PWR large-break LOCA, PWR small-break LOCA, and the BWR LOCA.

2.3.1. PWR Large-Break LOCA

The design basis accident is a double-ended guillotine break in a cold leg between the reactor coolant pump and the reactor vessel.

The blowdown period (0 – 30 s) is the result of a break in the coolant system through which the primary coolant is expelled. Within seconds after the break, the core voids and goes through departure from nuclear boiling. The negative void reactivity rapidly shuts down the core. With the diminished cooling and the redistribution of stored energy, the core heats up. Interactions between the pump and the break dynamics cause intermittent flow reversals. The primary system pressure rapidly decreases and the high-pressure safety injection begins. Injection from the cold-leg accumulators begins but much of the injected flow is swept around the downcomer, into the broken-loop cold leg. As the blowdown progresses an increasing amount of the injected coolant stays in the downcomer and some water begins to enter the lower plenum. The average blowdown peak cladding temperature (PCT) during the blowdown phase of the large-break LOCA is approximately 1500 °F and PCT at 95% confidence is about 1750 °F.

The refill period occurs between 30 and 40 s following the start of the LOCA. The primary pressure decreases to a level at which the low-pressure injection system activates and begins to inject water into the system. The lower plenum begins to fill with water as coolant bypass diminishes. While refilling of the lower plenum is underway, however, the core heats up in a near adiabatic mode due to decay heat. Some fuel rod bursting and blockage of flow channels can occur during refill.

The reflood period occurs between 40 and 200 s; it begins at the time when the lower plenum has filled and the core begins to refill. Water injected by the accumulators fills the downcomer and creates the driving head for refilling the core. The lower elevations of the core quench, generating a two-phase mixture that provides some cooling to the upper elevations of the core. However, the fuel rods continue to heat up until the quench front begins to move upward through the core. Some additional number of fuel rods may burst during the reflood period. Zirconium-water reactions can occur for high temperature regions of the core. As the quench front continues to advance, the fuel rod upper elevations are cooled by a dispersed non-equilibrium two-phase mixture of superheated steam and entrained droplets. Eventually, there is sufficient cooling in advance of the quench front to terminate the increase in cladding temperature and the PCT is reached. The average reflood PCT during this period is approximately 1680 °F and the PCT at 95% confidence is about 1975 °F. The maximum amount of cladding oxidized at a given location during this phase of the LOCA is about 10% and the total oxidation is less than 0.89%.

2.3.2. PWR Small-Break LOCA

Breaks with flow areas typically less than 1-ft^2 and greater than 3/8 in. span the category of small breaks. A small break is sufficiently large that the primary system depressurizes to the high pressure safety injection set point and a safety injection or "S" signal is generated, automatically starting the High Pressure Safety Injection (HPSI) system. Breaks smaller than 3/8-inch in diameter do not depressurize the reactor coolant system because the reactor charging flow can replace the lost inventory.

The limiting small-break LOCA is determined by the inter-play between core power level, the axial power shape, break size, the high-head safety injection performance, and the pressure at which the accumulator begins to inject. The limiting break is one that is large enough that the safety injection system cannot make-up the mass loss from the reactor system but small enough that the reactor system does not quickly depressurize to the accumulator set point. This combination of circumstances leads to a core uncovery.

For Westinghouse plants, the limiting breaks are typically in the 2-4 inch range. A spectrum of break sizes has been calculated for a Westinghouse three-loop plant. Calculations were performed assuming both fresh fuel and fuel with burnup between 30 and 54 GWd/t. Although the calculations were performed for different three-loop plants, they are thought to accurately display the effect of burnup on fuel performance.

With fresh fuel, a three-inch break was found to produce the highest PCTs for breaks in the range of 2 to 6 inches. The PCT of 1829 °F occurred at approximately 1480 s. The core average cladding oxidation was 0.53%. No bursting of the fuel is predicted for fresh fuel.

The available calculated results for fuel that has been in the reactor indicate that as burnup increases, some of the fuel will burst and experience double-sided cladding reactions. At 54 GWd/t, the hot rod PCT is predicted to be approximately 1500 °F.

2.3.3. BWR LOCA

The design basis accident for a BWR/6 is a double-ended break in the suction-side of the recirculation line.

Shortly after the break, the reactor scrams, typically on drive flow pressure. Because of the large flow reductions immediately following the LOCA caused by the depressurization, there is a rapid increase in the core average void fraction. The negative void reactivity rapidly shuts down the core. The flow reverses in the broken loop jet pump. With the flow reversal all the drive flow to that jet pump is lost and one-half the drive flow that is supporting the core flow is lost.

A loss of offsite power is also assumed. Thus, there is no power to the recirculation pump, which means that the intact loop pump also starts to coast down. The coast-down time of the pump is on the order of 10-15 seconds. With the loss of pumped flow, there is an almost instantaneous and large reduction in the core flow, which causes an early boiling transition in the core, typically within one second after the break.

The cladding temperature rapidly increases; the resulting blowdown peak cladding temperature is dominated by the stored energy in the fuel.

Valves are closed to isolate the system, typically within four seconds after the LOCA. System depressurization and loss of liquid inventory continue. As a result of the loss of inventory, the water level in the downcomer decreases and as the water level eventually drops down to the top of the jet pump. This opens a flow path through which steam can flow to the break. The rate of depressurization increases following jet pump uncovery.

During normal operation, the inlet subcooling at the bottom of the core is 20 °F. With the rapid depressurization, there is a large amount of flashing of the fluid in the lower plenum, this occurring at approximately 10 s. This causes a large increase coolant flow through the core, quenching the fuel, and returning the cladding temperature to the saturation temperature.

As the LOCA and depressurization continue, the level inside the core region decreases, as well as forming a level in the lower plenum region. The flow into the core is limited and the core uncovery leads to a second boiling transition. That typically happens at approximately 20 seconds into the transient.

Within 35-40 s following the LOCA, the high pressure core spray system begins to deliver coolant to the top of the core, the time being determined by the time to start the diesel generator that drives the high pressure core spray system. The low-pressure injection begins when the system pressure drops below the shutoff head for the pumps, typically on the order of about 200 psi.

A second transition and core heatup begins in the period 20-35 s. This heatup is terminated by the operation of the BWR-6 safety systems.

The BWR-6 has one high-pressure coolant system, one low-pressure core spray system, and three low-pressure coolant injection (LPCI) systems injecting into the bypass region. The worst single failure for the BWR-6 is the failure of one of the diesel generators that will drive two of the LPCI systems. The outcome of this failure is that the system behavior is based on the availability of the high-pressure core spray, the low pressure core spray and one LPCI system that injects into the bypass region.

Given the operation of these systems, the core refills before the lower plenum. The refilling and reflooding processes restores the liquid inventory in the core and quenches the core in the period 100-150 s following the LOCA. Throughout the transient, the best-estimate peak cladding temperature for nominal conditions is approximately 800 °F. The upper bound estimate for a 95%-95% upper bound is approximately 1200-1300 °F.

For the BWR/4, the ECC configuration is slightly different. However, The early part of the transient is very similar to the BWR/6. These differences cause the core reflood during the refilling and reflooding phase of the LOCA to take somewhat longer than in a BWR/6. This results in a somewhat higher peak cladding temperature for the BWR/4, with the peak cladding temperature for nominal conditions being approximately 1000 °F and the upper bound estimate approximately 1400-1500 °F.

The BWR/2 is the older-generation BWR without jet pumps. The core cannot be reflooded. The peak cladding temperature is controlled by a balance between decay heat and the core spray heat transfer. Typically, the peak cladding temperature occurs late in the transient, perhaps 600-800 s following the LOCA. Quenching of the fuel rods is also very slow. The upper bound peak cladding temperature for the BWR/2 is approximately 1700 °F.

For the purposes of this PIRT, the panel did not differentiate between BWR small-break and large-break LOCAs. The BWR is designed to automatically convert postulated small-breaks that would uncover the core into a large-break through the activation of an Automatic Depressurization System (ADS). The ADS opens several of the standard safety relief valves, causing a controlled depressurization with system response quite similar to that for a postulated large break in the reactor steam line.

2.3.2. Fuel and Cladding Behavior During a LOCA

Reactor power drops quickly when the coolant (moderator) is lost, but the fuel pellets have stored heat because of their heat capacity and radionuclide decay continues to provide an additional heat source. Consequently, the cladding temperature increases with time and the fuel pellet temperature decreases with time as the fuel and cladding temperatures tend to equilibrate. A qualitative plot of cladding temperature response to this transient is shown in Fig. 2-3. A more

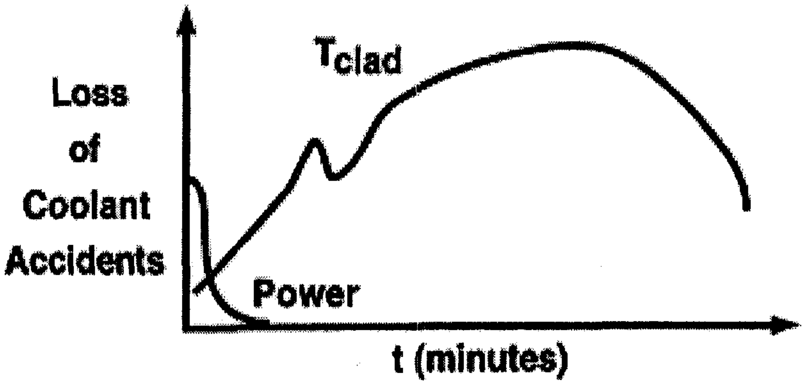

Fig. 2-3. Qualitative plot of fuel rod power and cladding temperature during a LOCA

quantitative plot of cladding temperature evolution with time is shown in Fig. 2-4, which is an idealized temperature profile that is being used for LOCA testing at Argonne National Laboratory. Following along this temperature profile, several important phenomena are identified.

As the cladding temperature reaches about 800 °C (1472 °F), ballooning of the cladding will take place because of the positive pressure differential and the elevated temperature. After reaching the ultimate tensile stress of the cladding, the ballooning process becomes unstable and rupture follows quickly. Fig. 2-5 shows the ballooned shape and cross section of a Zircaloy cladding tube that was ruptured in a simulation test. The extent of the ballooned region is of course important because large balloons would form blockages that might interfere with long-term cooling. Figure 2-6 shows the extent of ballooning deformation at the location of the burst for different degrees of azimuthal temperature uniformity. It is seen in this figure that variations in temperature, which are probably prominent in fresh fuel, lead to smaller ballooning strains.

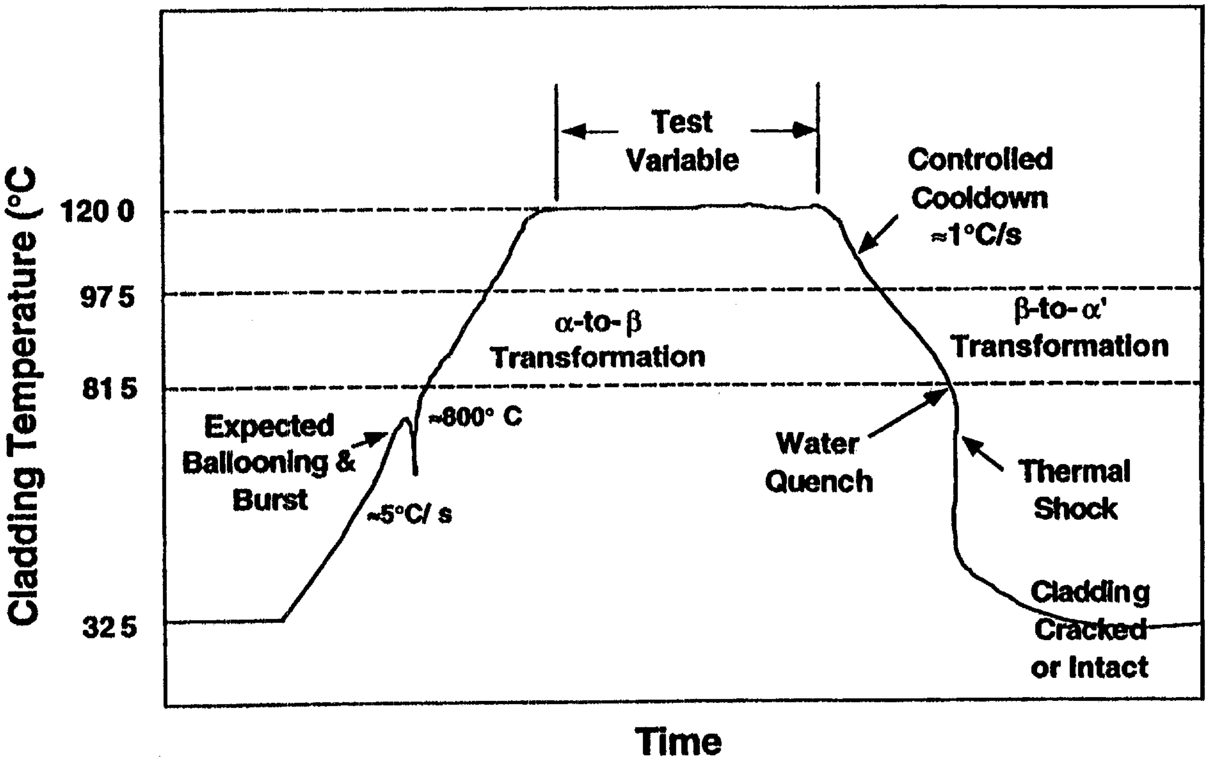

Fig. 2-4. Cladding temperature profile that is planned for LOCA testing at Argonne National Laboratory.

As the cladding temperature reaches about 800 °C (1472 °F), ballooning of the cladding will take place because of the positive pressure differential and the elevated temperature. After reaching the ultimate tensile stress of the cladding, the ballooning process becomes unstable and rupture follows quickly. Fig. 2-5 shows the ballooned shape and cross section of a Zircaloy cladding tube that was ruptured in a simulation test. The extent of the ballooned region is of course important because large balloons would form blockages that might interfere with long-term cooling. Fig. 2-6 shows the extent of ballooning deformation at the location of the burst for different degrees of azimuthal temperature uniformity. It is seen in this figure that variations in temperature, which are probably prominent in fresh fuel, lead to smaller ballooning strains.

Following rod burst, cladding temperature continues to rise to as much as 1200 °C (2200 °F limit from 10 CFR 50.46), at which temperature most of the cladding oxidation will take place. During this ascent in temperature, two important phenomena can take place. One is the relocation of pellet fragments into the ballooned region as seen in early tests in the PBF and FR-2 test reactors. This relocation of fuel material will increase the heat source in the ballooned region of the fuel. The other phenomenon is the phase transition in the Zircaloy cladding

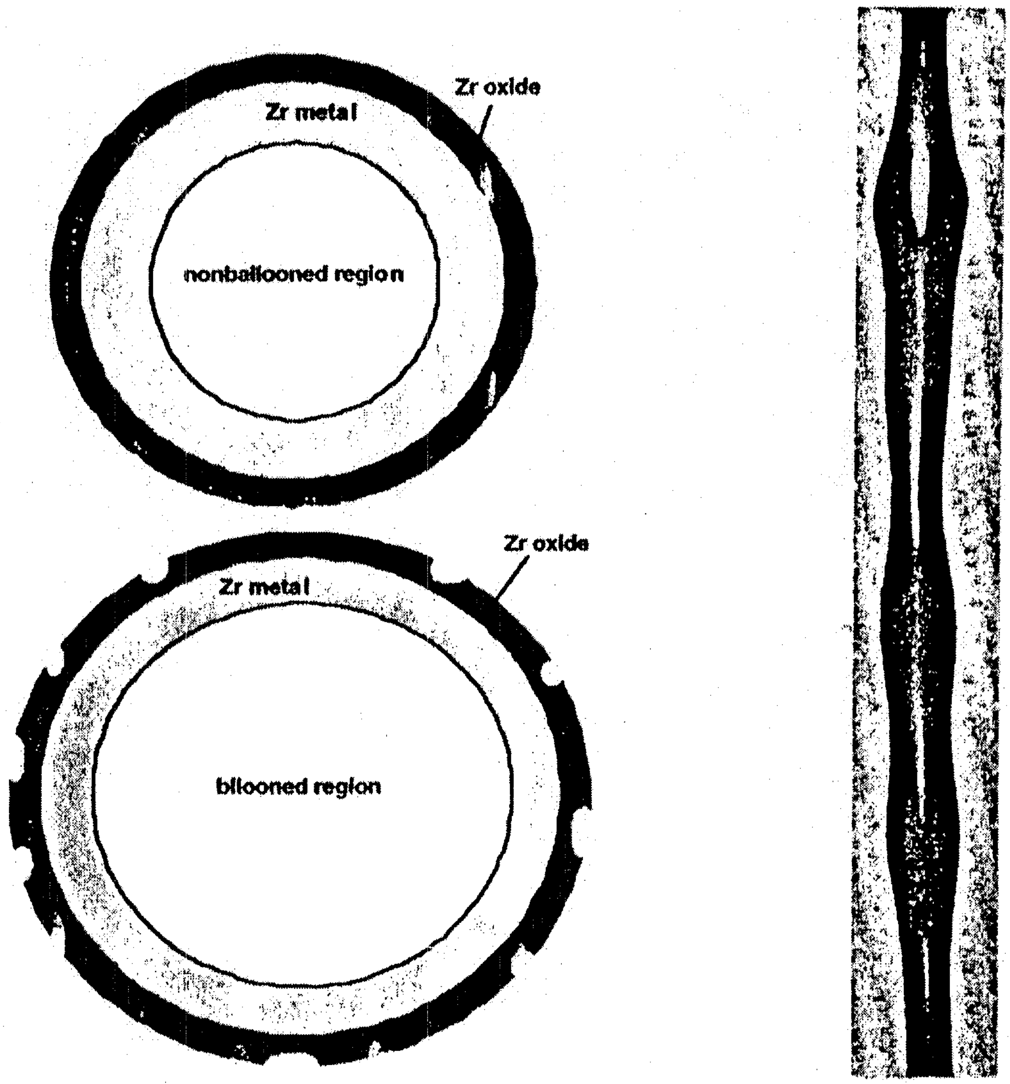

Fig. 2-5. Balloon shape and cross sections for Zircaloy cladding tube that was ruptured in a simulation test.

from the low temperature alpha phase to the high temperature beta phase. Figure 2-7 shows the phase diagram for these changes. A higher oxygen content makes the cladding material more susceptible to thermal shock failure.

At the end of the high temperature period, at which time as much as 17% of the original Zircaloy cladding may be oxidized (17% limit from 10 CFR 50.46), cooldown and quenching will occur. Because of reductions in ductility during the oxidation process, the thermal shock during quenching may fragment the cladding, or other mechanical loads may fragment the cladding after it has been fully quenched.

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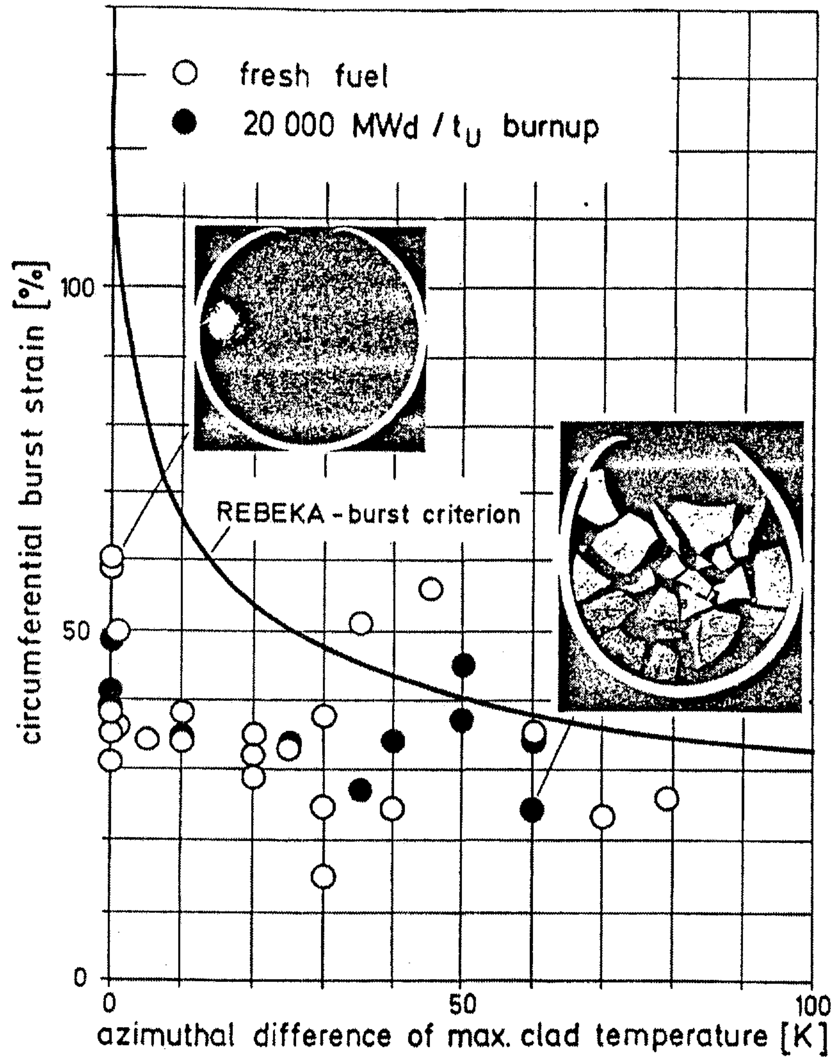

FIG. 24 - Burst strain of Zircaloy-4 cladding tubes versus azimuthal temperature difference (FR-2 in-pile versus REBEKA out-of-pile tests)

Fig. 2-6. Burst strain versus azimuthal temperature difference for Zircaloy cladding tubes ruptured in simulation tests

Figure 2-8 shows the microstructure and oxygen content expected prior to the LOCA transient. Here you see a large alpha-phase layer that has low oxygen content and

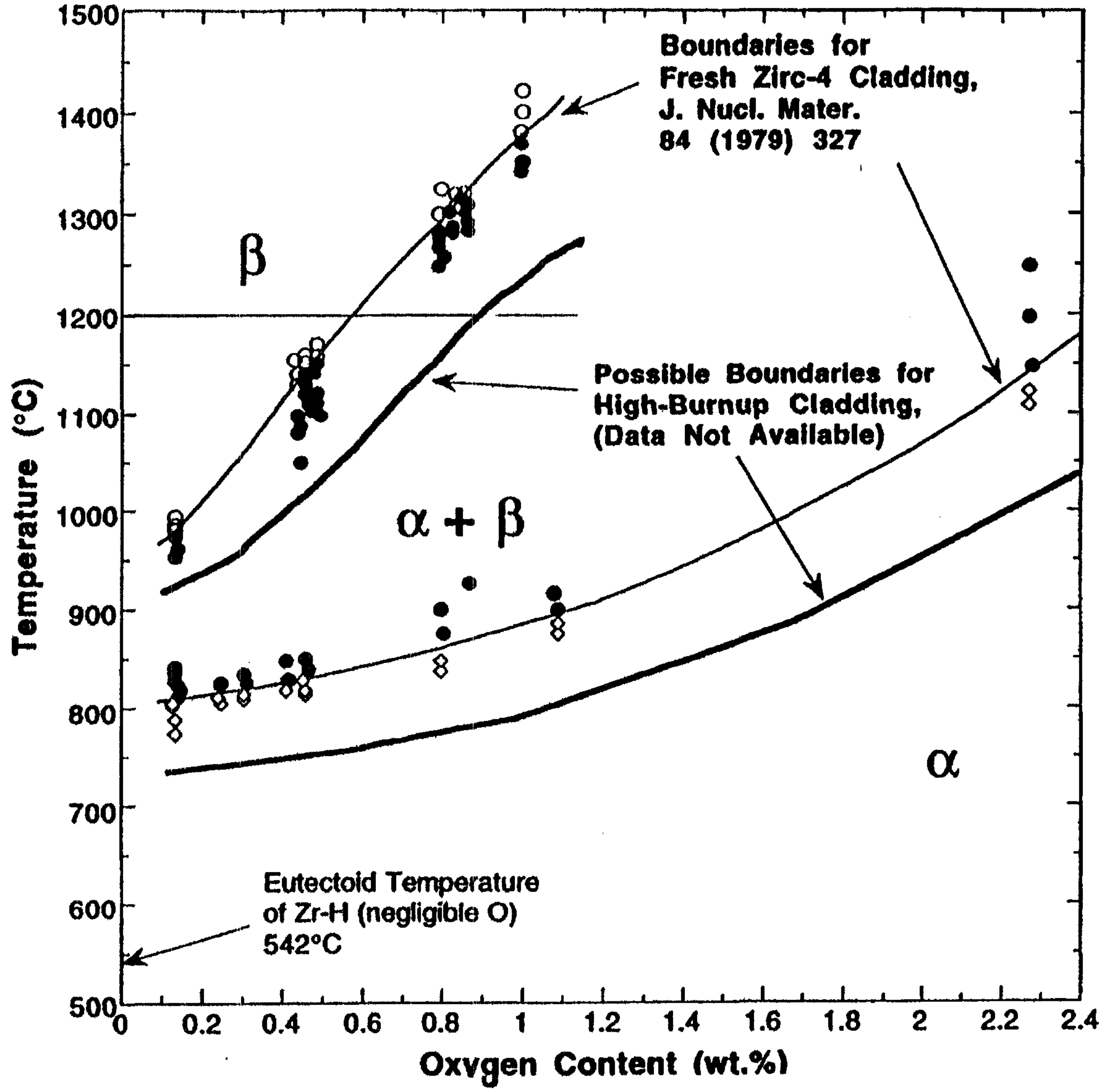

Fig. 2-7. Phase diagram for Zircaloy containing oxygen

high strength and ductility. Hydride stringers are shown in the cladding as discussed in connection with the reactivity accidents, but these hydrides would dissolve at subsequent high cladding temperatures during a LOCA. Figure 2-9 shows the microstructure and oxygen content right after the relatively slow cooldown but before the water quench. When you go back through the beta to-alpha phase transition, the alpha phase forms two layers. One alpha layer, right next to the oxide on both the OD and ID surfaces, has a very high oxygen content and has very low strength and ductility. This alpha layer cannot carry any significant load. The other layer, sometimes called the alpha-prime or prior-beta layer, has a low oxygen content and forms the surviving load-bearing thickness of the cladding. Whether fragmentation will occur depends largely on the thickness of this alpha-prime or prior-beta layer.

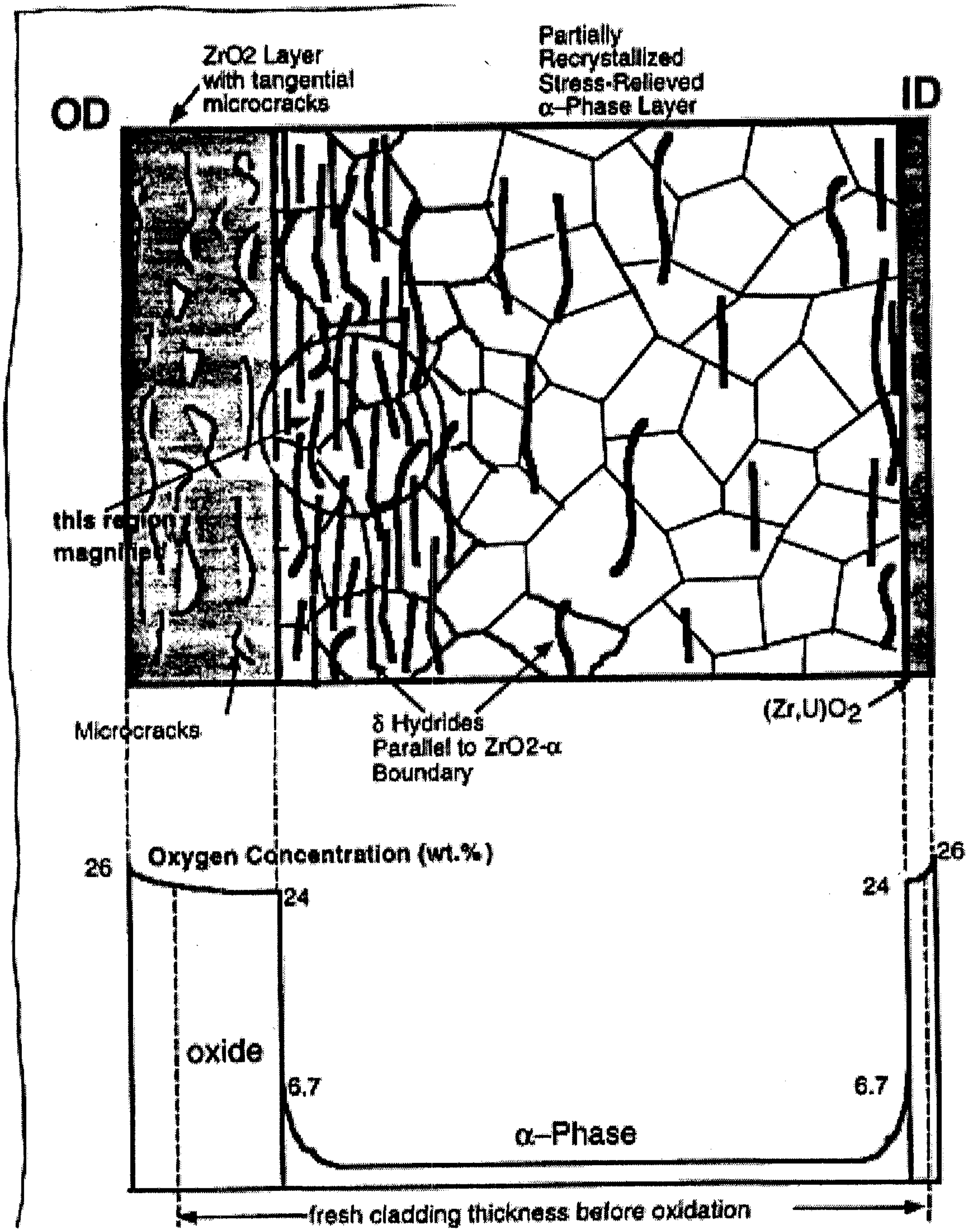

Fig. 2-8. Radial distribution of phases and oxygen concentration in Zircaloy prior to a LOCA transient.

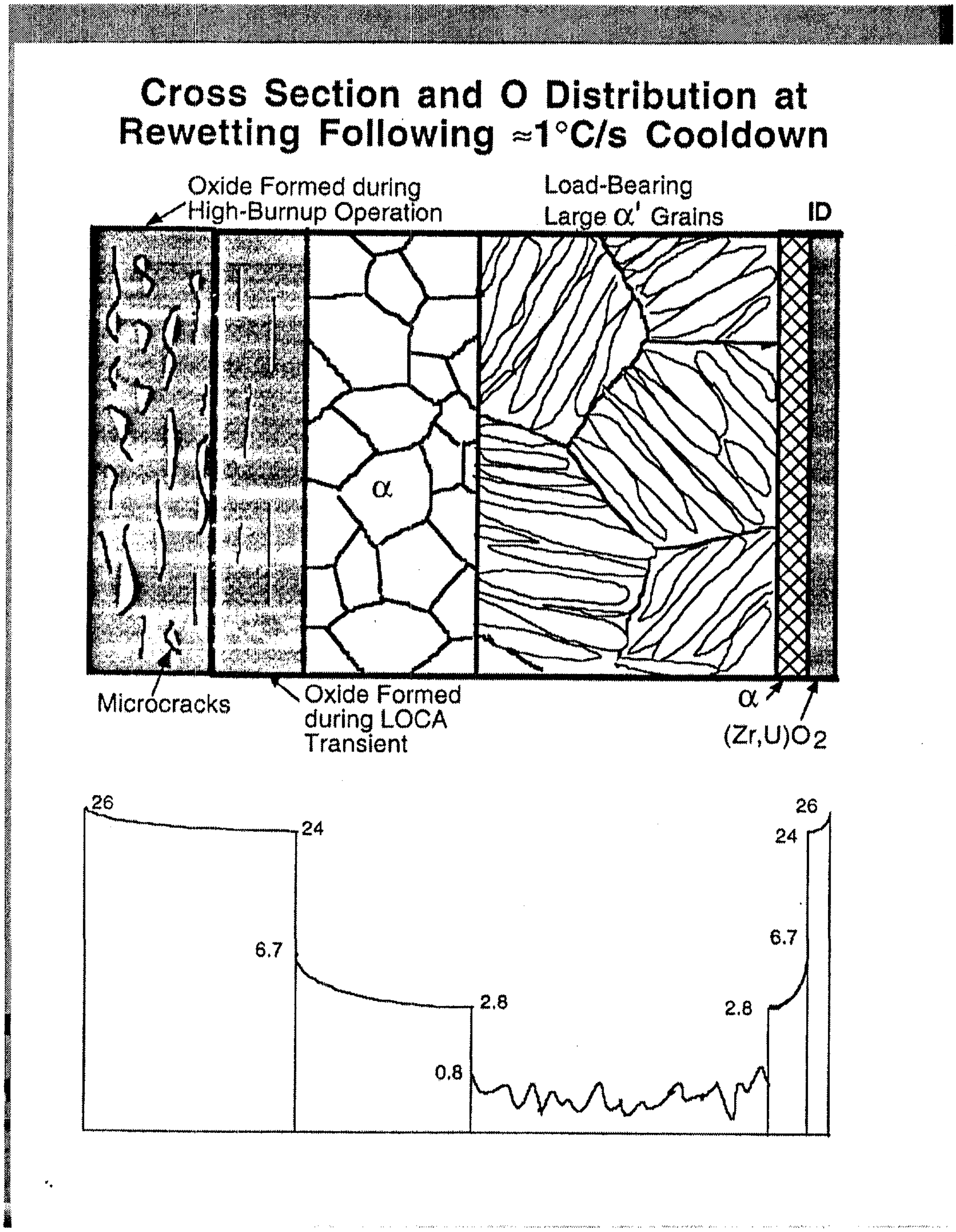

Fig. 2-9. Radial distribution of phases and oxygen concentration in Zircaloy after initial cooling from the peak cladding temperature but before the water quench.

2.4. Primary Evaluation Criterion

The main concern in the case of LOCA accidents is that they might lead to the loss of core coolability. At the high temperatures that can be encountered during a LOCA, the fuel rods can balloon, rupture, oxidize, and possibly melt. Upon cooling, the cladding would fragment and release fuel particles into the coolant. The dispersed fuel particles themselves could block flow channels and result directly in loss of coolable geometry.

Given this scenario, it is possible to associate the primary evaluation criterion with several significant physical phenomena associated with the sequence. These are:

A. Cladding fragmentation

B. Fuel dispersal

C. Channel blockage

It has been the traditional approach in reactor licensing to ensure that cladding fragmentation does not occur in order to guarantee long term core cooling. Hence, the primary evaluation criterion was chosen to be cladding fragmentation.

2.5. Categories of Phenomena

The panel recognized that, in order to resolve a LOCA issue by avoiding severe cladding failure, use will likely be made of a combination of analysis and experimental data. Given this reality, the panel generated a list of phenomena classified broadly into two analytical categories (Plant Analysis and Fuel Rod Analysis) and two experimental categories (Integral Experiments and Separate Effect Tests).

The four PIRT categories are as follows:

A. Plant Transient Analysis: includes the phenomena related to the plant-specific reactor kinetics, reactivity, and thermal-hydraulic response for the plant, as well as the transient thermal analysis of the fuel rod.

B. Integral Tests: includes the phenomena related to the integral testing of fuel rods, such as performed at Cabri and NSRR. This category is divided into fuel rod selection and conduct of the test.

C. Transient Fuel Rod Analysis: includes the phenomena and outcomes of calculations of transient fuel rod behavior such as performed by codes such as FRAPTRAN, FALCON and SCANAIR.

D. Separate Effect Tests: includes the important phenomena relevant to high- and low-temperature mechanical properties, phase transformations, fuel relocation, oxidation kinetics, cladding quenching, and seismic response in the post-accident condition.

The panel discussed at length the questions to be asked to determine the importance vote recorded in Section 3. For the most part the questions asked were as follows:

<u>Category A: Plant Transient Analysis</u>

Are the results of the code-calculated outcome (e.g., calculated peak power) sensitive to either this initial condition or to this phenomenon? If the answer is "yes," rank this item "high."

Category B: Integral Testing

Low temperature failures: If an integral test were to be conducted to investigate low temperature PCMI fuel behavior during a LOCA, is this phenomenon of high, medium, or low importance?

High temperature failures: If we were to conduct an integral in-pile or out-of-pile test to evaluate the effect of power and flow on transient critical heat flux (CHF) and the rewet temperature (T_{rewet}) for the LOCAs of interest, is this phenomenon of high, medium, or low importance?

Category C: Transient Fuel Rod Analysis

Are the results of the code-calculated outcome (e.g., cladding strain) sensitive to either this initial condition or to this phenomenon? If the answer is "yes," rank this item "high."

Is it important to the understanding and analysis derived from the code calculation that this parameter be calculated?

Category D: Separate Effect Tests

If a separate test were to be conducted to investigate low temperature PCMI fuel behavior during LOCAs of interest, is this phenomenon of high, medium, or low importance?

2.5. Phenomena Ranking Scale

It was decided that the low, medium, and high rank scheme should be adopted based upon past experience with the PIRT process.

- High = The phenomenon or process has dominant impact on the primary evaluation criterion, i.e., severe cladding failure with fuel dispersal, within the context of plant transient analysis, experimental testing, or transient fuel rod analysis. The phenomenon should be explicitly and accurately modeled in code development and assessment efforts. The phenomenon should be explicitly considered in any experimental programs.

- Medium = The phenomenon or process has moderate influence on the primary evaluation criterion. The phenomenon should be well modeled, but accuracy may be somewhat compromised in code development and assessment efforts. The phenomenon should also be considered in any experimental programs.

- Low = The phenomenon or process has small effect on the primary evaluation criterion. The phenomenon should be represented in the code, but almost any model will be sufficient. The phenomenon should be considered in any experimental programs to the extent possible.

Previous PIRTs have recorded a single importance rank for each phenomenon, with the option of recording any exceptions by a panel member with respect to a particular importance rank on a given phenomenon. The assignment of a single importance rank for a given phenomenon was achievable, in part, because the typical panel consisted of 6-8 members. Such panels were usually able to debate and move to a common view regarding phenomena importance in a timely manner.

The present panel has more than 20 members and the process of debating to a single importance rank for a given phenomenon was not deemed feasible. Given this situation, it was decided that a vote would be taken and the number of votes for each importance rank reported.

Panel members were asked to vote on only those phenomena for which they have a firm opinion about importance. Generally, the panel member's understanding of importance is understood to arise from direct experience. However, the panel members were free to vote based upon experience in related fields that permitted the panel member to see implications across different fields. Practically, this meant that not all of the panel members recorded ranking votes on some phenomena.

The rationales for voting "High," "Medium," or "Low" are recorded in Appendices A-D.

2.6. Extended PIRT Applicability

Recognizing that the value of the PIRTs would be enhanced if the applicability of the PIRTs to other reactor, fuel, cladding types, and higher burnups was assessed, the panel has considered and evaluated the applicability of the reactor- and fuel-specific PIRT to other reactor, fuel, cladding types, and higher burnups. The evaluation consisted of asking whether the importance ranks recorded for a given phenomenon would change for a different fuel array, specifically 8x8, 9x9, or 10x10, designated (F) in tables 3-1 to 3-4, a different cladding type from various vendors, e.g., GE and Siemens, designated (C), a different reactor type, e.g., BWR/2 – BWR/6, designated (R), and extended burnup to 75 GWd/t, designated (B). If the answer was "yes," an entry was made and the rationale reported. The outcome of the extended PIRT applicability assessment is reported as part of the PIRT tabulation.

2.7. Uncertainty Evaluation

The NRC requested that the panel consider the uncertainty relative to the panel's understanding of the phenomena. The panel did so for each phenomena by assigning uncertainty for the phenomena to one of three categories: "known" meaning approximately 75-100% of full knowledge and understanding of the phenomenon, "partially known" meaning approximately 25-75% of full knowledge and understanding of the phenomenon, and "unknown" meaning 0-25% of full knowledge and understanding of the phenomenon. The outcome of the uncertainty assessment was recorded and is reported as part of the PIRT tabulation.

2.8. References

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2-3. B. E. Boyack, J. G. M. Andersen, C. A. Alexander, B. M. Dunn, T. Fuketa, L. E. Hochreiter, R. O. Montgomery, F. J. Moody, A. T. Motta, K. L. Peddicord, G. Potts, D. W. Pruitt, J. Rashid, R. J. Rohrer, J. S. Tulenko, K. Valtonen, and W. Wiesenack, "Phenomenon Identification and Ranking Tables (PIRTs) Power Oscillations Without Scram in Boiling Water Reactors Containing High Burnup Fuel," Los Alamos National Laboratory document LA-UR-00-3122, Rev. 2 (October 11, 2000).

2-4. S. B. Wisner, R. B. Adamson, "Combined Effects of Radiation Damage and Hydrides on the Ductility of Zircaloy-2", Nuclear Engineering and Design, 185 (1998), pages 33-49.

3. PWR AND BWR LOCA PIRTS

Four PIRT tables are presented in this section, one each for Plant Transient Analysis, Integral Tests, Fuel Rod Transient Analysis, and Separate Effect Tests. The PIRT has been developed for PWR and BWR LOCA events in plants containing high burnup fuel. The plant and fuel, description of fuel and cladding state at high burnup, and accident scenario are described in Sections 2.1, 2.2, and 2.3, respectively. The selection of the four PIRT categories, as well as the phenomena definitions, is patterned after the PIRTs developed for a PWR rod ejection accident[3-1].

These PIRTs represent the informed judgment of the PIRT panel members regarding both the phenomena that are expected to occur during the scenario, and the relative importance of those phenomena. The importance of each phenomenon was evaluated relative to the primary evaluation criteria presented in Section 2.4, namely, severe cladding failure with fuel dispersal resulting from power oscillations. As discussed in Section 2.6, a vote was taken on the importance of each phenomenon and the number of panel members voting for "High," "Medium," and "Low" tabulated. The rationale for each vote has also been documented as discussed in Section 2.6.

The panel recognized that the phenomena lists presented in two related PIRT reports for reactivity transients[3-1, 3-2] primarily address low-temperature PCMI failure, and this is especially true for Categories C and D. Panel members concluded that fuel behavior for a high-temperature scenario for BWR power oscillations without scram would involve ballooning, rupture, oxidation, and fragmentation that would be quite similar to fuel behavior during a loss-of-coolant accident (LOCA). It was thus concluded that high-temperature behavior would be addressed only once, and the results would be recorded in this report on LOCA phenomena.

In addition to identifying and ranking phenomena, the applicability of the ranking vote for each phenomenon to other reactor, fuel and cladding types and to fuel burnups of 75 GWd/t was assessed as discussed in Section 2.7. Finally, the panel considered uncertainty relative to the panel's understanding of each phenomenon as discussed in Section 2.8.

3.1 Category Descriptions

Phenomena have been identified and ranked for importance relative to the evaluation criterion in each of the four following categories.

3.1.1. Category A: Plant Transient Analysis

The Plant Transient Analysis category includes the phenomena related to the plant-specific reactor kinetics and reactivity response for the plant, as well as the transient thermal analysis of the fuel rod, that are deemed relevant for understanding and predicting fuel behavior during PWR and BWR LOCAs. The PIRT for Plant Transient Analysis is provided in Table 3-1. This PIRT examines the phenomena that impact the calculation of power history during LOCAs and the calculation of fuel enthalpy increase during the event.

3.1.2. Category B: Integral Testing

The Integral Testing category includes the phenomena related to the integral testing of fuel rods. This category is further divided into three subcategories: fuel rod selection, conduct of the test, and parameters and variables measured. Fuel rod selection includes the initial conditions that are thought to be of importance in selecting fuel rods for use in integral tests, both in terms of capturing the important physical characteristics and in terms of assuring prototypicality of the testing. The Conduct of the test category captures the test features (either experimental design or parameters to be measured) that the panel deemed important for the integral tests. Parameters and variables measured identifies measurements taken either on-line or during post-test examination (PTE). The PIRT for Integral Testing is provided in Table 3-2.

3.1.3. Category C: Fuel Rod Transient Analysis

The Transient Fuel Rod Analysis category includes the phenomena and outcomes of calculations of transient fuel rod behavior predicting the fuel behavior in reactor integral tests and in separate effect tests. These calculations are performed with codes such as FRAPTRAN, FALCON and SCANAIR.[3-1, Appendix G]. This category is divided into seven sub-categories that may require modeling in the codes. The first (initial conditions) captures the characteristics of the fuel and cladding before the transient. The remaining five sub-categories (transient boundary conditions, fuel rod response, multiple rod mechanical effects, properties, and transient cladding-to-coolant heat transfer) simulate the loading, and the thermal, mechanical response of the fuel and cladding that need to be modeled by the code to assess fuel failure during a LOCA. The PIRT for Transient Fuel Rod Analysis is provided in Table 3-3.

3.1.4. Category D: Separate Effect Testing

The Separate Effect Testing category was developed by considering the types of separate effect experiments that might be conducted to develop needed data. The panel defined six test types and the phenomena associated with each. Prior to voting on the phenomena themselves, the panel voted on the importance of each test type. The order of presentation of the test types in Table 3-4 is in the order of importance assigned by the working group that developed Category D. The number of votes for each test type is presented in column 1 of Appendix D. The test types are briefly described below.

- Oxidation rate, oxygen distribution, effect of chemistry on solubility. Such tests would measure the steam oxidation kinetics at high temperature in Zirconium alloys used for cladding.
- Quench tests, including quench rate and time of quench. These tests would determine the thermal shock resistance of cladding when quenched after high-temperature oxidation.
- Phase equilibria and transformation kinetics-chemistry. These tests would measure phase equilibria and phase transformation kinetics to provide fundamental data relevant to the cladding behavior during LOCA events.
- Mechanical properties at high temperature, e.g., > 300 °C. These tests would be designed to investigate creep and burst behavior of cladding at high temperature.

Creep and burst tests, uniaxial tests, and post oxidation and quench ductility tests were considered.

- Seismic tests would address the ability of the fuel rod to withstand a post-LOCA seismic event using the four-point bending test.
- Simulation of fuel relocation. These tests would balloon and burst a high burnup rod and determine the fuel relocation and posttest thermal conductivity.

3.2. Structure of the PIRT Tables

The structure of each PIRT-results table is:

- Column 1—Subcategory, a collector for related phenomena. An importance vote is taken at the subcategory level only if there are no phenomena associated with the subcategory.

- Column 2— Phenomenon being ranked.

- Column 3 — Phenomenon importance rank. The number of panel members voting for High (H), Medium (M), and Low (L) are tabulated in the respective columns. The total number of panel members voting on given phenomena varies as discussed in Section 2.5. The ranking scale is also described in Section 2.5. The importance ranking (IR) is also tabulated here and described below in Sect. 3.4.

- Column 4 — Extended applicability assessment. Panel assessment of whether the importance assessment for the base case appearing in column 3 will be altered for other fuel, cladding, reactor types, or fuel with a burnup of 75 GWd/t. A "Y" or "yes" communicates that the importance ranking will be altered while an "N" or "no" indicates that importance ranking will not be altered.

- Column 5 —Uncertainty evaluation. The number of panel members voting for known (K), partially known (PK), or unknown (UK) is tabulated in the respective columns. The definitions for K, PK, and UK are appended to the table. See references in Section 2.7 for additional details. The knowledge ratio (KR) is also tabulated here and described below in Section 3.4.

3.3. Phenomena Descriptions and Ranking Rationales

Phenomena descriptions and ranking rationales are given in tabular form in Appendices A-D. Appendix A presents all the descriptions and rationales for Category A, plant transient analysis. Appendix B presents all the descriptions and rationales for Category B, integral testing, and so forth. These large tables are, in effect, annotated versions of the PIRT tables that will follow in this section.

3.4. Panel Analysis of PIRT Results

The panel has examined the results of the PIRT effort to identify the most important outcomes. The panel's observations are summarized by category below. The importance rankings and rationales, combined with the uncertainty rankings and rationales, have been considered in developing the panel's perspective regarding the important issues affecting PWR and BWR LOCAs.

The panel notes that our approach to developing PIRTs for high burnup fuel evolved during the course of the PIRT effort. This was due to several factors. First, the membership of this PIRT panel was much larger than previous PIRT panels. Given the size of the panel, it was more difficult to have sufficient exchanges to develop a common understanding of processes and definitions. For example, we note that two different questions were answered at different points of the PIRT process as the uncertainty rankings, i.e., K, PK, or UK, were developed. One was "How well do we know the parameter in question?" and the other was "How well do we know the *effect* of the parameter in question on transient behavior?" As both questions were addressed at various times, we have identified which question the panel was addressing when knowledge or uncertainty regarding each phenomenon subcategory was addressed.

To provide a weighting structure to our assessment of the importance and uncertainty vote results, we created the Importance Ratio (IR) and the Knowledge Ratio (KR). This was accomplished by assigning a value of 1 to a "High" or "Known" vote, a value of 0.5 to "Medium" or "Partially Known" vote and a value of zero to a "Low" or "Unknown" vote.

The importance ratio is:

$$IR = 100 \times (H + M/2)/(H+M+L)$$

where H, M and L stand for the number of high, medium and low votes, and the knowledge ratio is:

$$KR=100 \times (K + PK/2)/(K+PK+UK)$$

where K, PK and UK stand for the number of known, partially known and unknown votes respectively.

We applied the importance ratio, IR, by considering any phenomenon with an importance ratio, IR, greater than 75 to be highly important.

We applied the knowledge ratio, KR, by considering any phenomenon with a knowledge ratio of less than 75 to have associated with a significant *lack of knowledge,* i.e., the closer the IR value is to zero, the greater the lack of knowledge.

The cutoff values for the IR and KR are arbitrary, but the panel believes that use of these cutoff values does accurately convey the panel's perspective regarding those phenomena for which the importance is high relative to the evaluation criterion but for which there is a significant lack of knowledge.

3.4.1. Category A: Plant Transient Analysis

The "Plant Transient Analysis" category consists of seven subcategories, Initial conditions, Transient power distribution, Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood) and core spray heat transfer, Transient conditions as a function of elevation and time, Fuel rod response, Multiple rod mechanical effects, and Multiple rod thermal effects.

Within the "Initial conditions" subcategory, gas pressure and rod free volume met the dual criteria on IR and KR, i.e., having an IR greater than 75 and a KR less than 75. These phenomena are, therefore, flagged as candidates for additional consideration.

Within the "Transient power distribution" subcategory, several phenomena were identified as being highly important but none met the dual criteria on IR and KR. No phenomenon in this subcategory was, therefore, flagged as a candidate for additional consideration.

Within the "Steady state and transient cladding to coolant heat transfer" subcategory, film boiling, rewet, rod-to-spacer grid thermal-hydraulic interaction, and spacer grid rewetting and droplet breakup met the dual criteria on IR and KR. These phenomena are, therefore, flagged as candidates for additional consideration.

Within the "Transient coolant conditions as a function of elevation and time" subcategory, temperature, flow rate and direction (CCFL), quality, void fraction, and cross flow effects due to flow blockage met the dual criteria on IR and KR. These phenomena are, therefore, flagged as candidates for additional consideration.

Within the "Fuel rod response" subcategory, cladding temperature, burst criteria, location of burst and blockage, and time dependent gap-size heat transfer met the dual criteria on IR and KR. These phenomena are, therefore, flagged as candidates for additional consideration.

Within the "Multiple rod mechanical effects" subcategory, no phenomenon was identified as being either highly important or lacking knowledge. No phenomenon in this subcategory was, therefore, flagged as a candidate for additional consideration.

Within the "Multiple rod thermal effects" subcategory, several phenomena were identified as being highly important but none met the dual criteria on IR and KR. No phenomenon in this subcategory was, therefore, flagged as a candidate for additional consideration.

3.4.2 Category B: Integral Testing

This category collects the phenomena related to integral testing in facilities such as Cabri, NSRR, and Halden. As discussed in Section 3.1.2, this category is further subdivided into three subcategories, Fuel rod selection, Conduct of the test, and parameters and variables measured.

Within the "Fuel rod selection" subcategory, fuel burnup and cladding as-fabricated wall thickness met the dual criteria on IR and KR, i.e., having an IR greater than 75 and a KR less than 75. These phenomena are, therefore, flagged as candidates for additional consideration.

Within the "Conduct of test" subcategory, plateau temperature, cooldown and quench and rewet rate initiation, and fuel or non-fuel testing configuration met the dual criteria on IR and KR. These phenomena are, therefore, flagged as candidates for additional consideration.

Within the "parameters and variables measured" subcategory, PTE examination for (1) fuel relocation and residual bonding and dispersal and (2) PTE examination for chemistry, i.e., total hydrogen and oxygen content met the dual criteria on IR and KR. These phenomena are, therefore, flagged as candidates for additional consideration.

3.4.3. Category C: Transient Fuel Rod Analysis

The "Transient Fuel Rod Analysis" category consists of six subcategories: initial conditions, transient boundary conditions, fuel rod response, multiple rod mechanical effects, properties, and transient cladding-to-coolant heat transfer.

Within the "Initial conditions" subcategory, gas pressure, gas composition, cladding oxidation, hydrogen concentration, hydrogen distribution, porosity distribution, rim size, and spallation and cracking of the oxide layer met the dual criteria on IR and KR, i.e., having a IR greater than 75 and a KR less than 75. These phenomena are, therefore, flagged as candidates for additional consideration.

Within the "Transient boundary conditions" subcategory, transient cladding-to-coolant heat transfer and transient coolant conditions met the dual criteria on IR and KR. These phenomena are, therefore, flagged as candidates for additional consideration.

Within the "Fuel rod response" subcategory, heat resistances in the gap and oxide, cladding oxidation magnitude, size of burst opening, burst criteria, and time of burst met the dual criteria on IR and KR. These phenomena are, therefore, flagged as candidates for additional consideration.

Within the "Multiple rod mechanical effects" subcategory, the single phenomenon was identified as being either highly important or lacking knowledge. It was not, therefore, flagged as a candidate for additional consideration.

Within the "Properties" subcategory, no phenomenon was identified as being both highly important and lacking knowledge. No phenomenon in this subcategory was, therefore, flagged as a candidate for additional consideration.

Within the "Transient cladding-to-coolant heat transfer" subcategory, rod-to-spacer thermal-hydraulic interactions and spacer grid rewetting and droplet breakup met the dual criteria on IR and KR. These phenomena are, therefore, flagged as candidates for additional consideration.

3.4.4. Category D: Separate Effect Testing

This category collects the phenomena related to separate effect testing. It is important to have these tests to translate the results from the integral tests and to help explore the possible variations in parameters. The panel identified parameters that should be measured in a separate effect test to aid in the interpretation of the test and to develop a mechanistic understanding of the failure process.

As discussed in Section 3.1.4, this category is divided into six subcategories, each consisting of a test type. The six subcategories are oxidation rate, oxygen distribution, effect of chemistry on solubility; quench tests, including quench rate and time of quench; phase equilibria and transformation kinetics-chemistry; Mechanical properties at high temperature; seismic tests; and simulation of fuel relocation.

Within the "Oxidation rate" subcategory, oxygen potential and temperature and time during the test and oxygen distribution during post test examination (PTE) met the dual criteria on IR and KR, i.e., having a IR greater than 75 and a KR less than 75. These phenomena are, therefore, flagged as candidates for additional consideration.

Within the "Quench tests" subcategory, specimen selection for hydrogen content and distribution; axial constraints, cladding with fuel or empty, clad temperature before quench, temperature history and pre-thinning of cladding and preburst during the test; and determination of fragmentation and characterization of tubing integrity during PTE met the dual criteria on IR and KR. These phenomena are, therefore, flagged as candidates for additional consideration.

Within the "Phase equilibria and transformation kinetics-chemistry effect" subcategory, specimen selection for alloy type, determination of hydrogen and oxygen solubilities, and determination of retained beta and transformed beta-phase morphology and oxygen plus hydrogen redistribution met the dual criteria on IR and KR. These phenomena are, therefore, flagged as candidates for additional consideration.

Within the "Mechanical properties at high temperature" subcategory, specifically creep and burst tests, specimen selection for alloy and initial thermo-mechnical treatment and hydrogen content and strain profile and biaxiality ratio met the dual criteria on IR and KR. For the uniaxial test, specimen selection for alloy type and initial thermomechanical heat treatment and hydrogen content and fluence met the dual criteria on IR and KR. These phenomena are, therefore, flagged as candidates for additional consideration.

Within the "Seismic test" subcategory, specimen selection for alloy type, thickness and morphology of pre-existing and transient oxides, pre-existing and transient hydrogen content and distribution, and ballooning met the dual criteria on IR and KR. For test conduct, temperature, strain rate, ASTM specification, appropriate bending moment, and cycling met the dual criteria on IR and KR. For PTE tests, characterization of integrity and local hydrogen met the dual criteria on IR and KR. These phenomena are, therefore, flagged as candidates for additional consideration.

Within the "Simulation of fuel relocation" subcategory, specimen selection for burnup and chemical and mechanical bonding met the dual criteria on IR and KR. For test conduct, internal pressure and moles of gas and balloon size and burst size met the dual criteria on IR and KR. For PTE tests, granularity of dispersed material, strain profile of the cladding and burst size met the dual criteria on IR and KR. These phenomena are, therefore, flagged as candidates for additional consideration.

3.5. References

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3-2. B. E. Boyack, J. G. M. Andersen, C. A. Alexander, B. M. Dunn, T. Fuketa, L. E. Hochreiter, R. O. Montgomery, F. J. Moody, A. T. Motta, K. L. Peddicord, G. Potts, D. W. Pruitt, J. Rashid, R. J. Rohrer, J. S. Tulenko, K. Valtonen, and W. Wiesenack, "Phenomenon Identification and Ranking Tables (PIRTs) Power Oscillations Without Scram in Boiling Water Reactors Containing High Burnup Fuel," Los Alamos National Laboratory document LA-UR-00-3122, Rev. 2 (October 11, 2000).

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Table 3-1

PWR AND BWR LOCA Category A – Plant Transient Analysis PIRT

		Importance[2]				Applicability[3,4]				Uncertainty[5,6]			
Subcategory	Phenomena[1]	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Initial conditions	Gap size	7	0	0	100	N	N	N	N	7	0	0	100
	Gas pressure	7	0	0	100	N	N	N	N	0	7	0	50
	Gas composition	1	6	0	57	Y	N	N	N	0	7	0	50
	Pellet and cladding dimensions	0	7	0	50	N	N	N	N	7	0	0	100
	Burnup distribution	7	0	0	100	N	N	N	N	7	0	0	100
	Cladding oxidation (ID & OD)	0	0	7	0	N	N	N	N	0	7	0	50
	Coolant conditions	7	0	0	100	N	N	N	N	7	0	0	100
	Rod free volume	7	0	0	100	N	N	N	N	0	7	0	50
	Gas communication (full)	0	2	5	14	N	N	N	Y	0	7	0	50
	Gadolinium distribution (conductivity effect)	0	0	7	0	N	N	N	N	7	0	0	100
	Initial stored energy-fuel	7	0	0	100	N	N	N	N	7	0	0	100
	Initial stored energy-structures	7	0	0	100	N	N	N	N	7	0	0	100
	Initial core pressure drop (grids)	0	0	7	0	N	N	N	N	7	0	0	100
	Pellet radial power distribution	0	0	7	0	N	N	N	N	7	0	0	100
	Rod axial power distribution	7	0	0	100	N	N	N	N	7	0	0	100
	Fuel assembly peaking factors	7	0	0	100	N	N	N	N	7	0	0	100
	Pin peaking factors	0	1	6	7	N	N	Y	N	7	0	0	100
	Fuel cycle design	7	0	0	100	N	N	N	N	7	0	0	100
Transient power distribution	Moderator feedback	7	0	0	100	N	N	N	N	7	0	0	100
	Decay heat power	7	0	0	100	N	N	N	N	7	0	0	100

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Table 3-1

PWR AND BWR LOCA Category A – Plant Transient Analysis PIRT

		Importance[2]				Applicability[3,4]				Uncertainty[5,6]			
Subcategory	Phenomena[1]	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Transient power distribution (cont)	Fuel temperature feedback	0	0	7	0	N	N	N	N	7	0	0	100
	Delayed neutron fraction	0	0	7	0	N	N	N	N	7	0	0	100
	Fractional energy deposition in moderator and structures	0	0	7	0	N	N	Y	N	7	0	0	100
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood) and core spray heat transfer	Single phase convection	7	0	0	100	N	N	N	N	7	0	0	100
	Subcooled boiling, nucleate boiling, bulk boiling, and forced convectcion vaporization	7	0	0	100	N	N	N	N	7	0	0	100
	Critical heat flux/dryout	7	0	0	100	Y	N	N	N	7	0	0	100
	Film boiling over a wide void fraction (inverted annular, dispersed flow)	7	0	0	100	N	N	N	N	0	7	0	50
	Radiation heat transfer to coolant	0	0	7	0	N	N	N	N	7	0	0	100
	Rewet	7	0	0	100	N	N	N	N	0	7	0	50
	Rod-to-spacer grid thermal-hydraulic interaction	6	1	0	93	Y	N	N	N	0	7	0	50
	Spacer grid rewetting and droplet breakup	7	0	0	100	Y	N	N	N	0	0	7	0
Transient coolant conditions as a function of elevation and time	Temperature	7	0	0	100	N	N	N	N	0	7	0	50
	Flow rate/directions (CCFL)	7	0	0	100	N	N	N	N	0	7	0	50

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Table 3-1

PWR AND BWR LOCA Category A – Plant Transient Analysis PIRT

		Importance[2]				Applicability[3,4]				Uncertainty[5,6]			
Subcategory	Phenomena[1]	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Transient coolant conditions as a function of elevation and time (cont)	Quality	7	0	0	100	N	N	N	N	0	7	0	50
	Void fraction	7	0	0	100	N	N	N	N	0	7	0	50
	Pressure	7	0	0	100	N	N	N	N	7	0	0	100
	Partial vapor pressure	0	0	7	0	N	N	N	N	7	0	0	100
	Cross flow effects due to flow blockage	7	0	0	100	N	N	N	N	0	7	0	50
Fuel rod response	Plastic deformation of cladding (thinning, ballooning and burst)	5	0	0	100	N	Y	N	N	5	0	0	100
	Direct gas pressure loading	5	0	0	100	N	N	N	N	3	2	0	80
	Thermal deformation of pellet and cladding	0	0	5	0	N	N	N	N	5	0	0	100
	Elastic deformation of cladding	0	3	2	30	N	N	N	N	5	0	0	100
	Heat resistances in fuel, gap and cladding	5	0	0	100	N	N	N	N	5	1	0	92
	Axial and radial temperature distributions	5	0	0	100	N	N	N	N	5	1	0	92
	Metal-water reaction heat addition	0	1	5	8	N	N	N	N	5	0	0	100
	Cladding oxidation magnitude	0	0	5	0	N	N	N	N	4	1	0	90
	Cladding temperature	5	0	0	100	N	N	N	N	3	2	0	70
	Burst criteria	5	0	0	100	N	N	N	N	0	5	0	50
	Cladding phase changes	0	4	1	40	N	N	N	N	5	0	0	100
	Time of burst	1	4	1	60	N	N	N	N	0	5	0	50
	Location of burst and blockage	5	0	0	100	N	N	N	N	4	2	0	71
	Fuel relocation	0	2	4	20	N	N	N	N	0	0	5	0

Table 3-1
PWR AND BWR LOCA Category A – Plant Transient Analysis PIRT

		Importance[2]				Applicability[3,4]				Uncertainty[5,6]			
Subcategory	Phenomena[1]	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Fuel rod response (cont)	Time dependent gap-size heat transfer	5	0	0	100	N	N	N	N	1	5	0	58
	Thermal and mechanical properties of pellet and cladding	5	0	0	100	N	N	N	N	5	0	0	100
Multiple rod mechanical effects	Rod-to-rod mechanical interactions	0	1	4	10	N	N	N	N	0	0	4	0
	Rod bow between spacer grids	0	0	4	0	N	N	N	N	0	0	4	0
Multiple rod thermal effects	Rod-to-rod radiative heat transfer	0	0	4	0	N	N	Y	N	4	0	0	100
	Rod-to-channel box radiative heat transfer	4	0	0	100	N	N	NA	N	4	0	0	100
	Rod-to-spacer grid local heat transfer	1	4	0	60	N	N	N	N	0	4	0	50
	Rod-to-guide tube radiative heat transfer	0	0	4	0	N	N	NA	N	4	1	0	90
	Rod-to-water rod radiative heat transfer	4	1	0	90	N	N	N	N	5	0	0	100
	Rod-to-inner channel radiative heat transfer	4	1	0	90	N	N	N	N	5	0	0	100

1. Descriptions for the phenomena listed in the Plant Transient Analysis PIRT are provided in Appendix A.
2. The rationale for each High, Medium and Low rank are documented in Appendix A.
3. The column numbers are related to the following issues related to extended applicability
   F = Fuel array, i.e., 8x8; 9x9, or 10x10 rods in a fuel assembly, chamfer, or MOX
   C = Cladding types from various vendors, e.g., GE and Siemans, barrier-type or not.
   R = Reactor type, e.g., BWR/2 through /6.
   B = Burnup to 75 GWd/t. Data received by ballot. "N" entered if none voted "Yes". Otherwise, the number of "Yes" votes entered.
4. The rationale for "Y" entries, meaning cases in which the importance ranking will be altered from the base case rankings in columns 3-5, are documented in Appendix A.
5. The definitions for Known, Partially Known, and Unknown used by the panel are as follows.
   K = Known; approximately 75-100% of full knowledge and understanding
   PK = Partially known; 30-70% of full knowledge and understanding
   UK = Unknown; approximately 0-25% of full knowledge and understanding

The rationale for the assessment of uncertainty is found in Appendix A.

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Table 3-2

PWR and BWR LOCA Category B – Experimental Testing PIRT

			Importance[2]				Applicability[3,4]				Uncertainty[5,6]			
Subcategory	Phenomena[1]		H	M	L	IR	F	C	R	B	K	PK	UK	KR
Fuel rod selection	Fuel	Burnup	5	1	0	92	N	N	N	N	0	6	0	50
		PU agglomerates (MOX fuel only)	1	0	6	14	NA	N	N	N	6	0	1	86
		Duty cycle	0	4	3	29	N	N	N	N	4	3	0	79
		Fuel type (absorbers, additives	0	3	4	21	NA	N	N	N	0	4	2	33
	Cladding:	Pre-existing oxidation (thickness, type, uniformity f[θ])	2	4	1	57	N	N	N	N	6	1	0	93
		Spalling	0	3	4	21	N	N	N	N	2	5	0	64
		Total hydrogen	3	4	0	71	N	N	N	N	4	3	0	79
		Hydrogen distribution	0	1	5	8	N	N	N	N	5	1	0	92
		Surface conditions (crud)	0	1	5	8	N	N	N	N	5	1	0	92
		Fluence/radiation damage	0	1	5	8	N	N	N	N	5	1	0	92
		Initial residual deformation (hourglassing, creepdown)	0	2	4	17	N	N	N	N	0	5	1	42
		Chemical bonding	1	4	1	50	Y	N	N	N	0	5	1	42
		As-fabricated wall thickness	3	1	0	88	N	Y	N	N	2	2	0	75
	Cladding Alloy type:	Alloy composition Microstructure/2nd phase particle Initial cold work Liner/nonliner clad	2	4	1	57	N	NA	N	N	0	4	2	33

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Table 3-2
PWR and BWR LOCA Category B – Experimental Testing PIRT

		Importance[2]				Applicability[3,4]				Uncertainty[5,6]			
Subcategory	Phenomena[1]	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Conduct of test	Plateau temperature (plus variations)	7	0	0	100	N	N	N	N	3	4	0	71
	Temperature ramp	3	4	0	71	N	N	N	N	4	3	0	79
	Time at temperature	7	0	0	100	N	N	N	N	7	0	0	100
	Cooldown/quench/rewet rate initiation: (Clad temperature level, mass flow rate, pump or gavity feed, quality, subcooling)	6	1	0	93	N	N	N	N	2	5	0	64
	Plenum volume	1	5	0	58	N	N	N	N	6	1	0	93
	Internal pressure	3	3	0	75	N	N	N	N	4	3	0	79
	Attachments	1	6	0	57	N	N	N	N	5	2	0	86
	Temperature measurement	7	0	0	100	N	N	N	N	6	1	0	93
	Gas composition	0	1	6	7	N	N	N	N	7	0	0	100
	Design test such that axial and azimuthal temperature gradients are known	3	4	0	71	N	N	N	N	4	2	0	71
	Single rod versus bundle	1	3	3	36	N	N	N	N	0	6	0	50
	Fuel/nonfuel	7	0	0	100	N	N	N	N	2	5	0	54
	Water chemistry	0	6	1	43	N	N	N	N	7	0	0	100
	Coolant flow conditions	0	3	4	21	N	N	N	N	6	1	0	93
	Heating source (internal or external, type, electrical, radiant, neutronic)	3	4	0	71	N	N	N	N	6	1	0	93
	Specimen length	2	5	0	64	N	N	N	N	6	1	0	93
	Specimen constraints (grids, spacers, structures)	7	0	0	100	N	N	N	N	5	2	0	86

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Table 3-2

PWR and BWR LOCA Category B – Experimental Testing PIRT

Subcategory	Phenomena[1]		Importance[2] H	M	L	IR	Applicability[3,4] F	C	R	B	Uncertainty[5,6] K	PK	UK	KR
Conduct of test (cont)	Temperature effects of fuel relocation		3	3	1	64	Y	N	N	N	4	3	0	79
	Fuel stored energy		1	1	3	30	N	N	N	N	5	2	0	86
Parameters/variables measured	Online:	Clad temperature f(θ , z, t)	7	0	0	100	N	N	N	N	4	3	0	79
		Fuel temperature f(z, t)	0	4	3	29	N	N	N	N	4	2	1	71
		Time of failure	6	1	0	93	N	N	N	N	5	2	0	86
		Time of fuel relocation	2	2	3	43	N	N	N	N	0	6	1	43
		Fuel dispersal	0	5	2	36	N	N	N	N	0	3	3	25
		Internal pressure (value and axial communication)	3	3	1	64	N	N	N	N	2	4	0	67
		Hydrogen release/evolution	0	3	4	21	N	N	N	N	5	2	0	86
		Fission product release	1	4	2	43	N	N	N	N	5	0	2	71
		Steam consumption	2	1	4	36	N	N	N	N	4	3	0	79
		Strain measurement	2	3	2	50	N	N	N	N	4	3	0	79
	PTE:	ECR at failure location (burst and/or thermal shock)	7	0	0	100	N	N	N	N	5	2	0	86
		Remaining prior beta thickness	6	1	0	93	N	N	N	N	4	3	0	79
		Cladding strain	3	4	0	71	N	N	N	N	4	2	0	71
		Fuel relocation, residual bonding and/or dispersal	7	0	0	100	Y	N	N	N	0	3	2	30
		Metallography (oxide thickness microstructure, prior beta, hydrides, and cladding thinning)	7	0	0	100	N	N	N	N	5	2	0	86

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Table 3-2
PWR and BWR LOCA Category B – Experimental Testing PIRT

Subcategory	Phenomena[1]	Importance[2] H	M	L	IR	Applicability[3,4] F	C	R	B	Uncertainty[5,6] K	PK	UK	KR
Parameters/variables measured (continued)	Chemistry (Total hydrogen and oxygen content)	7	0	0	100	N	N	N	N	4	2	0	71
	Oxide spallation and delamination during test	0	1	6	7	N	N	N	N	3	2	0	80
	Fission gas distribution	0	2	4	17	Y	N	N	N	0	3	0	50

1. Descriptions for the phenomena listed in the Experimental Testing PIRT are provided in Appendix B.
2. The rationale for each High, Medium and Low rank are documented in Appendix B.
3. The column numbers are related to the following issues related to extended applicability
   F = Fuel array, i.e., 8x8; 9x9, or 10x10 rods in a fuel assembly, chamfer, or MOX
   C = Cladding types from various vendors, e.g., GE and Siemans, barrier-type or not.
   R = Reactor type, e.g., BWR/2 through /6.
   B = Burnup to 75 GWd/t. Data received by ballot. "N" entered if none voted "Yes". Otherwise, the number of "Yes" votes entered.
4. The rationale for "Y" entries, meaning cases in which the importance ranking will be altered from the base case rankings in columns 3-5, are documented in Appendix B.
5. The definitions for Known, Partially Known, and Unknown used by the panel are as follows.
   K = Known; approximately 75-100% of full knowledge and understanding
   PK = Partially known; 30-70% of full knowledge and understanding
   UK = Unknown; approximately 0-25% of full knowledge and understanding
6. The rationale for the assessment of uncertainty is found in Appendix B.

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Table 3-3

PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

		Importance[2]				Applicability[3,4]				Uncertainty[5,6]			
Subcategory	**Phenomena[1]**	**H**	**M**	**L**	**IR**	**F**	**C**	**R**	**B**	**K**	**PK**	**UK**	**KR**
Initial conditions	Gap size	5	0	0	100	N	N	N	N	5	0	0	100
	Gas pressure	6	0	0	100	N	N	N	N	0	5	0	50
	Gas composition	5	0	0	100	N	N	N	N	0	5	0	50
	Pellet and cladding dimensions	5	0	0	100	N	N	N	N	5	0	0	100
	Burnup distribution	5	0	0	100	N	N	N	N	5	0	0	100
	Cladding oxidation (ID + OD)	6	0	0	100	N	N	N	N	2	4	0	50
	Hydrogen concentration	5	0	1	83	N	N	N	N	2	3	0	70
	Hydrogen distribution	5	0	1	83	N	N	N	N	2	3	0	70
	Fast fluence	5	0	0	100	N	N	N	N	5	0	0	100
	Porosity distribution	5	0	1	83	N	N	N	N	0	5	0	50
	Rim size	5	0	1	83	Y	N	N	N	0	5	0	50
	Pellet radial power distribution	0	5	0	50	N	N	N	N	5	0	0	100
	Rod axial power distribution	5	0	0	100	N	N	N	N	5	0	0	100
	Fuel-clad gap friction coefficient (bonding)	0	3	2	30	N	N	N	Y	0	5	0	50
	Surface conditions (rewet)	1	0	5	17	N	N	N	N	5	1	0	92
	Coolant conditions (P, T, α, x, mdot)	5	0	0	100	N	N	N	N	5	0	0	100
	Rod free volume	5	0	0	100	N	N	N	N	5	0	0	100
	Gas communication (resistance)	0	1	5	8	N	N	N	N	5	0	0	100
	Pu cluster size (MOX only)	0	0	5	0	NA	N	N	N	5	0	0	100
	Pellet cracking representation	0	5	0	50	N	N	N	N	5	1	0	92

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Table 3-3

PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

		Importance[2]				Applicability[3,4]				Uncertainty[5,6]			
Subcategory	Phenomena[1]	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Initial conditions (cont)	Gadolinium distribution (conductivity effect)	0	5	0	50	Y	N	N	N	5	0	0	100
	Initial stored energy	5	0	0	100	N	N	N	N	5	0	0	100
	Initial core pressure drop (grids)	0	0	5	0	N	N	N	N	5	0	0	100
	Spallation of oxide layer, cracking	5	1	0	92	N	Y	N	N	0	5	0	50
	Pellet shape	0	0	5	0	N	N	N	N	5	1	0	92
Transient boundary conditions	Transient cladding-to-coolant heat transfer (all phases: blowdown refill, reflood and steady state)	5	0	0	100	N	N	N	N	0	5	0	50
	Transient and steady state power distributions	5	0	0	100	N	N	N	N	5	0	0	100
	Transient coolant conditions	5	0	0	100	N	N	N	N	0	5	0	50
Fuel rod response	Plastic deformation of cladding (thinning, ballooning and burst)	5	0	0	100	N	N	N	N	4	1	0	90
	Direct gas pressure loading	5	0	0	100	N	N	N	N	5	0	0	100
	Quench loading of clad	0	3	2	30	N	N	N	N	5	1	0	92
	Thermal deformation of pellet and cladding	0	0	5	0	N	N	N	N	5	0	0	100
	Elastic deformation of cladding	0	4	1	40	N	N	N	N	5	0	0	100
	Fission gas release	0	0	5	0	N	N	N	N	5	0	0	100
	Pellet swelling	0	0	5	0	N	N	N	N	5	0	0	100
	Axial and radial temperature distributions	5	0	0	100	N	N	N	N	5	0	0	100
	Heat resistances - fuel	5	0	0	100	N	N	N	N	4	2	0	83
	Heat resistances - gap	5	0	0	100	N	N	N	N	0	6	0	50
Fuel rod response (cont)	Heat resistances - clad	1	5	0	58	N	N	N	N	5	0	0	100

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Table 3-3
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

		Importance[2]				Applicability[3,4]				Uncertainty[5,6]			
Subcategory	Phenomena[1]	H	M	L	IR	F	C	R	B	K	PK	UK	KR
	Heat resistances - oxide	5	1	0	92	N	Y	N	N	0	5	0	50
	Cladding azimuthal temperature distributions	1	5	0	58	N	N	N	N	0	6	0	50
	Cladding oxidation magnitude (ID/OD)	5	0	0	100	N	N	N	N	2	4	0	67
	Metal-water reaction heat addition	5	1	0	92	N	N	N	Y	6	0	0	100
	Size of burst opening	6	0	0	100	N	N	N	N	0	5	1	42
	Burst criteria	6	0	0	100	N	N	N	N	1	5	0	58
	Cladding phase changes	6	0	0	100	N	N	N	N	6	0	0	100
	Time of burst	6	0	0	100	N	N	N	N	0	6	0	50
	Location of burst	6	0	0	100	N	N	N	N	4	2	0	83
	Spacer grid constraint	1	3	2	36	N	N	N	Y	0	6	0	50
	Pellet to cladding bonding	2	4	0	50	N	N	N	N	0	6	0	50
	Localized effects	0	0	5	0	N	N	N	Y	0	0	5	0
	Biaxiality	0	2	3	30	N	N	N	N	5	0	0	100
	Fuel relocation	1	5	0	58	N	N	N	N	0	6	0	50
	Grain boundary decohesion	0	0	5	0	N	N	N	N	0	5	0	50
	Evolution of pellet stress state	0	0	5	0	N	N	N	N	5	0	0	100
Multiple rod mechanical effects	Rod-to-rod and rod-to-channel thermal and mechanical interactions	1	5	0	58	N	N	Y	N	5	0	0	100

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Table 3-3
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

		Importance[2]				Applicability[3,4]				Uncertainty[5,6]			
Subcategory	Phenomena[1]	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Properties	Fracture stress of oxide	0	0	5	0	N	N	N	N	5	0	0	100
	Yield stress in compression	0	0	5	0	N	N	N	N	5	0	0	100
	Heat capacities of fuel and cladding	5	0	0	100	N	N	N	N	5	0	0	100
	Thermal conductivities of fuel and cladding	5	0	0	100	N	N	N	N	5	0	0	100
	Strain rate effects	0	0	5	0	N	N	N	N	5	0	0	100
	Anisotropy	0	0	5	0	N	N	N	N	5	0	0	100
Transient cladding-to-coolant heat transfer	Rod-to-spacer grid thermal-hydraulic interaction	5	0	0	100	N	N	N	N	0	5	0	50
	Spacer grid rewetting and droplet breakup	5	0	0	100	N	N	N	N	0	5	0	50

1. Descriptions for the phenomena listed in the Transient Fuel Rod Analysis PIRT are provided in Appendix C.
2. The rationale for each High, Medium and Low rank are documented in Appendix C.
3. The column numbers are related to the following issues related to extended applicability
   - F = Fuel array, i.e., 8x8; 9x9, or 10x10 rods in a fuel assembly, chamfer, or MOX
   - C = Cladding types from various vendors, e.g., GE and Siemans, barrier-type or not.
   - R = Reactor type, e.g., BWR/2 through /6.
   - B = Burnup to 75 GWd/t. Data received by ballot. "N" entered if none voted "Yes". Otherwise, the number of "Yes" votes entered.
4. The rationale for "Y" entries, meaning cases in which the importance ranking will be altered from the base case rankings in columns 3-5, are documented in Appendix C.
5. The definitions for Known, Partially Known, and Unknown used by the panel are as follows.
   - K = Known; approximately 75-100% of full knowledge and understanding
   - PK = Partially known; 30-70% of full knowledge and understanding
   - UK = Unknown; approximately 0-25% of full knowledge and understanding

   The rationale for the assessment of uncertainty is found in Appendix C.

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Table 3-4

PWR and BWR LOCA Category D – Separate Effect Testing PIRT

		Importance[2]				Applicability[3,4]				Uncertainty[5,6]			
Subcategory	**Phenomena[1]**	**H**	**M**	**L**	**IR**	**F**	**C**	**R**	**B**	**K**	**PK**	**UK**	**KR**
Oxidation rate, oxygen distribution, effect of chemistry on solubility	Specimen selection: Alloy type	3	2	0	80	N	NA	N	N	3	2	0	80
	Specimen selection: Thickness and morphology of pre-existing oxide	1	2	2	40	N	NA	N	N	2	3	0	70
	Specimen selection: Burnup, including fluence	3	1	1	70	N	N	N	NA	1	4	0	60
	Specimen selection: Pre-existing hydrogen content and distribution	1	3	1	50	N	NA	N	NA	2	2	0	75
	Conduct of Test-During Oxygen potential	3	1	0	88	N	N	N	N	1	2	0	67
	Conduct of Test-During Temperature and time	5	0	0	100	N	N	N	N	2	2	0	75
	Conduct of Test-During Total steam pressure	0	3	1	38	N	N	N	N	3	1	0	88
	Conduct of Test-During Weight gain	4	1	0	90	N	N	N	N	5	0	0	100
	Conduct of Test-During Steam consumption	1	2	2	40	N	N	N	N	3	2	0	80
	Conduct of Test-During One-sided vs. two-sided	2	2	1	60	N	N	N	N	2	3	0	70
	Conduct of Test-PTE Oxide thickness	5	0	0	100	N	N	N	N	3	1	0	88
	Conduct of Test-PTE Chacteristic α–β morphology	5	0	0	100	N	N	N	N	3	2	0	80

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Table 3-4

PWR and BWR LOCA Category D – Separate Effect Testing PIRT

Subcategory	Phenomena[1]	Importance[2]				Applicability[3,4]				Uncertainty[5,6]			
		H	M	L	IR	F	C	R	B	K	PK	UK	KR
Oxidation rate, oxygen distribution, effect of chemistry on solubility (cont)	Conduct of Test-PTE Oxygen distribution	5	0	0	100	N	N	N	N	2	2	0	75
	Conduct of Test-PTE Hydrogen pickup and distribution	3	2	0	80	N	N	N	Y	3	2	0	80
Quench tests, quench rate, Tquench, etc.	Specimen selection: Hydrogen content and distribution	2	2	0	75	N	N	N	N	2	2	0	75
	Specimen selection: Alloy type	2	1	1	63	Y	N	Y	N	1	2	1	83
	Specimen selection: Thickness and morphology of pre-existing oxide	2	2	1	60	N	N	N	N	3	1	1	70
	Specimen selection: Burnup	2	3	1	58	Y	N	N	N	2	2	1	60
	Conduct of Test-During Axial constraints	5	0	0	100	N	N	N	N	0	4	1	40
	Conduct of Test-During Azimuthal quenching	1	3	1	50	N	N	N	N	0	4	1	40
	Conduct of Test-During Empty/full	3	2	0	80	N	N	N	Y	1	4	0	60
	Conduct of Test-During One-sided vs two-sided	1	4	0	60	N	N	N	N	1	4	0	60
	Conduct of Test-During Cooldown before quench	5	0	0	100	N	N	N	N	3	2	0	80

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Table 3-4

PWR and BWR LOCA Category D – Separate Effect Testing PIRT

Subcategory	Phenomena[1]	Importance[2] H	M	L	IR	Applicability[3,4] F	C	R	B	Uncertainty[5,6] K	PK	UK	KR
Quench tests, quench rate, Tquench, etc. (cont)	Conduct of Test-During Clad temperature before quench	4	1	0	90	N	N	N	N	2	3	0	70
	Conduct of Test-During Cycling of quenching	1	2	2	40	N	N	N	N	0	2	3	20
	Conduct of Test-During Temperature history	3	2	0	80	N	N	N	N	2	3	0	70
	Conduct of Test-During Pre-thinning of cladding/pre-burst	3	2	0	80	N	N	N	N	2	2	0	75
	Conduct of Test-During Quench mass flow rate	0	1	3	13	N	N	N	N	0	4	0	50
	Conduct of Test-PTE Equivalent cladding reacted (ECR) at location of failure	6	0	0	100	N	N	N	N	4	2	0	83
	Conduct of Test-PTE Metallography	5	0	0	100	N	N	N	N	3	2	0	80
	Conduct of Test-PTE Fragment/non-fragment	5	0	0	100	N	N	N	N	2	3	0	70
	Conduct of Test-PTE Characterization of tubing integrity	4	1	0	90	N	N	N	N	2	3	0	70

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Table 3-4

PWR and BWR LOCA Category D – Separate Effect Testing PIRT

Subcategory	Phenomena[1]	Importance[2] H	Importance[2] M	Importance[2] L	Importance[2] IR	Applicability[3,4] F	Applicability[3,4] C	Applicability[3,4] R	Applicability[3,4] B	Uncertainty[5,6] K	Uncertainty[5,6] PK	Uncertainty[5,6] UK	Uncertainty[5,6] KR
Phase equilibria and transformation kinetics-chemistry effects	Specimen selection: Hydrogen content and distribution	4	1	0	90	N	Y	N	Y	3	2	0	80
	Specimen selection: Alloy type	4	1	0	90	N	N	Y	N	2	3	0	70
	Specimen selection: Oxygen content	2	3	0	70	N	N	N	N	4	1	0	90
	Specimen selection: Fluence	0	2	3	20	N	Y	N	N	2	3	0	70
	Determination of hydrogen and oxygen solubilities in α and β phases as a function of hydrogen, oxygen, and temperature for relevant alloys	4	1	0	90	N	Y	N	Y	1	4	0	60
	Determination of rate constants for rate-limiting transport mechanisms for phase transformation during heating as a function of hydrogen, heating rate and cooling rate	3	1	1	70	N	N	N	N	2	3	0	70
	Determination of diffusion coefficient of oxygen in individual phases	1	1	1	50	N	N	N	N	2	1	0	83
	Determination of the retained β and transformed β-phase morphology and oxygen plus hydrogen redistribution during β - α transformations (cooling), including Niobium-rich alloys	2	0	0	100	N	N	N	N	0	2	0	50

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Table 3-4
PWR and BWR LOCA Category D – Separate Effect Testing PIRT

Subcategory	Phenomena[1]	Importance[2] H	M	L	IR	Applicability[3,4] F	C	R	B	Uncertainty[5,6] K	PK	UK	KR
Mechanical Properties at high temperature, e.g., ≥ 300 C Creep and burst tests	Specimen selection: Pre-existing oxide	1	2	1	50	N	N	N	N	4	0	0	100
	Specimen selection: Alloy and initial thermo-mechanical treatment	4	1	0	90	N	Y	N	N	2	2	1	60
	Specimen selection: Hydrogen content	1	4	0	75	N	Y	N	N	1	4	0	60
	Specimen selection: Fluence (radiation damage)	1	1	3	30	N	N	N	N	3	2	0	80
	Conduct of Test-During Strain profile as a f(r, θ, z, t)	3	1	0	88	N	N	N	N	3	1	0	70
	Conduct of Test-During Pressure as f(t)	4	0	1	80	N	N	N	N	3	2	0	80
	Conduct of Test-During Temperature as f(t)	5	0	0	100	N	N	N	N	4	1	0	90
	Conduct of Test-During Temperature profile as f(θ) and f(z)	4	1	0	90	N	N	N	N	3	2	0	80
	Conduct of Test-During Open (actively pressurized) or closed	3	1	1	70	N	N	N	N	4	1	0	90
	Conduct of Test-During Biaxiality ratio	3	1	0	88	N	N	N	N	2	2	0	75

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Table 3-4
PWR and BWR LOCA Category D – Separate Effect Testing PIRT

		Importance[2]				Applicability[3,4]				Uncertainty[5,6]			
Subcategory	Phenomena[1]	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Mechanical Properties at high temperature, e.g., ≥ 300 C Creep and burst tests (cont)	Conduct of Test-PTE Post-test strain (fractographic)	4	0	1	80	N	N	N	N	3	2	0	80
Mechanical Properties at high temperature, e.g., ≥ 300 C Uniaxial test	Specimen selection: Alloy type and initial thermomechanical heat treatment	3	0	0	100	N	N	N	N	1	1	1	50
	Specimen selection: Hydrogen content	3	0	0	100	N	N	N	N	1	2	0	67
	Specimen selection: Oxygen content	1	2	0	75	N	N	N	N	2	1	0	83
	Specimen selection: Fluence	2	1	0	83	N	N	N	N	1	2	0	67
	Conduct of Test-During Load and displacements, i.e., σ and ε behavior	5	0	0	100	N	N	N	N	3	2	0	80
	Conduct of Test-During Total elongation, post-test	4	0	0	100	N	N	N	N	2	1	0	83
	Conduct of Test-During Temperature and temperature rate	2	0	1	67	N	N	N	N	2	1	0	83
	Conduct of Test-During Strain rate	2	1	0	83	N	N	N	N	2	1	0	83
	Conduct of Test-During Circumferential (hoop)/axial (ring)	2	1	0	83	N	N	N	N	2	1	0	83

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Table 3-4
PWR and BWR LOCA Category D – Separate Effect Testing PIRT

		Importance[2]				Applicability[3,4]				Uncertainty[5,6]			
Subcategory	**Phenomena[1]**	**H**	**M**	**L**	**IR**	**F**	**C**	**R**	**B**	**K**	**PK**	**UK**	**KR**
Mechanical Properties at high temperature, e.g., ≥ 300 C Post oxidation and quench ductility test	Test types (1) Axial tensile (2) Ring tensile (3) Ring compression (4) Impact (5) Bending	4	1	1	75	N	N	N	N	1	3	0	63
Seismic tests 4-point bending	Specimen selection: Alloy type	4	0	0	100	N	Y	N	N	1	1	2	25
	Specimen selection: Thickness and morphology of pre-existing and *transient oxides*	3	1	0	88	N	N	N	N	3	0	1	75
	Specimen selection: Burnup	2	1	1	63	N	N	N	N	2	1	1	63
	Specimen selection: Pre-existing and transient hydrogen content and distribution	4	0	0	100	N	N	N	N	2	1	1	63
	Specimen selection: With or without ballooning	4	0	0	100	N	N	N	N	1	2	0	67
	Conduct of Test-During Temperature	3	0	1	75	N	N	N	N	0	4	0	50
	Conduct of Test-During Strain rate (displacement ratio)	3	1	0	88	N	N	N	N	0	3	0	50
	Conduct of Test-During ASTM specification	2	1	0	83	N	N	N	N	1	3	0	63
	Conduct of Test-During Appropriate bending moment	4	0	0	100	N	N	N	N	1	3	0	63

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Table 3-4
PWR and BWR LOCA Category D – Separate Effect Testing PIRT

		Importance[2]				Applicability[3,4]				Uncertainty[5,6]			
Subcategory	Phenomena[1]	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Seismic tests (cont) 4-point bending	Conduct of Test-During Cycling	3	0	1	75	N	N	N	N	1	3	0	63
	Conduct of Test-PTE Characterize integrity	4	0	0	100	N	N	N	N	1	1	2	25
	Conduct of Test-PTE Characterize local hydrogen	4	0	0	100	N	N	N	Y	1	2	0	67
Simulation of fuel relocation	Specimen selection: Burnup	4	0	0	100	Y	N	N	N	1	3	0	63
	Specimen selection: Fuel type (MOX)	2	1	1	63	N	N	N	N	1	2	1	50
	Specimen selection: Alloy type	2	2	1	60	N	N	N	N	2	1	1	63
	Specimen selection: Chemical and mechanical bonding	4	0	0	100	N	N	N	N	0	3	1	38
	Specimen selection: Cracking	2	0	2	50	N	N	N	N	1	3	0	63
	Conduct of Test-During With or without blowdown	0	1	2	17	N	N	N	N	0	1	2	17
	Conduct of Test-During Blowdown temperature transients for fuel and cladding	2	0	1	67	N	N	N	N	1	2	0	67
	Conduct of Test-During Pre- and post-burst test phases (2)	1	3	0	63	N	N	N	N	1	3	0	63
	Conduct of Test-During Internal pressure and moles of gas	3	1	0	88	N	N	N	N	0	4	0	50
	Conduct of Test-During Flow induced vibration	0	2	2	25	N	N	N	N	0	2	1	33

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Table 3-4
PWR and BWR LOCA Category D – Separate Effect Testing PIRT

Subcategory	Phenomena[1]	Importance[2] H	M	L	IR	Applicability[3,4] F	C	R	B	Uncertainty[5,6] K	PK	UK	KR
Simulation of fuel relocation (cont)	Conduct of Test-During Exterior rod constraints	1	1	2	38	Y	N	N	N	0	4	0	50
	Conduct of Test-During Balloon size and burst size	4	0	1	80	N	N	N	N	1	2	0	67
	Conduct of Test-During Length	2	1	1	63	N	N	N	N	1	3	0	63
	Conduct of Test-PTE Granularity of dispersed material	3	1	0	88	N	N	N	N	0	4	0	50
	Conduct of Test-PTE Thermography	1	0	2	33	N	N	N	N	0	2	1	33
	Conduct of Test-PTE Thermal diffusivity of rubble bed	1	1	1	50	N	N	N	N	0	2	1	33
	Conduct of Test-PTE Strain profile of cladding as f(r,z)	3	1	0	88	N	N	N	N	1	3	0	63
	Conduct of Test-PTE Burst size	3	0	1	75	N	N	N	N	2	2	0	75
	Conduct of Test-PTE Material balance (in-rod and dispersed)	2	0	2	50	N	N	N	N	1	2	1	50

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Table 3-4

PWR and BWR LOCA Category D – Separate Effect Testing PIRT

1. Descriptions for the phenomena listed in the Separate Effect Testing PIRT are provided in Appendix D.
2. The rationale for each High, Medium and Low rank are documented in Appendix D.
3. The column numbers are related to the following issues related to extended applicability

   F = Fuel array, i.e., 8x8; 9x9, or 10x10 rods in a fuel assembly, chamfer, or MOX

   C = Cladding types from various vendors, e.g., GE and Siemans, barrier-type or not.

   R = Reactor type, e.g., BWR/2 through /6.

   B = Burnup to 75 GWd/t. Data received by ballot. "N" entered if none voted "Yes". Otherwise, the number of "Yes" votes entered.
4. The rationale for "Y" entries, meaning cases in which the importance ranking will be altered from the base case rankings in columns 3-5, are documented in Appendix D.
5. The definitions for Known, Partially Known, and Unknown used by the panel are as follows.

   K = Known; approximately 75-100% of full knowledge and understanding

   PK = Partially known; 30-70% of full knowledge and understanding

   UK = Unknown; approximately 0-25% of full knowledge and understanding

   The rationale for the assessment of uncertainty is found in Appendix D.

4. DATABASES

Although identification and ranking of processes and phenomena rely heavily on the expertise of the PIRT panel, both of these efforts proceed best when there are comprehensive databases of information upon which judgements are based. The experimental databases used by the PWR and BWR LOCA PIRT panel are documented in Section 4.1. The analytical databases used by the panel are documented in Section 4.2.

4.1. Experimental Databases

A variety of separate effect and integral experimental programs seeking a better understanding of the phenomena occurring in high burnup fuel during a PWR rod ejection accident have been conducted or are in the process of being conducted. That information was summarized in the PWR rod ejection report PIRT report.[4-1] Although some of the information therein may be of value, it is specific to PWR fuel, cladding and conditions. Additional tests with BWR fuel were summarized in the BWR ATWS PIRT report.[4-2] Test programs delivering data that is directly applicable to the PWR and BWR LOCA PIRT panel are summarized in this section and more detailed descriptions of these experimental programs are presented in Appendix E.

4.1.1. Separate Effect Tests

Separate effect tests are experiments in which a limited number of physical phenomena of interest occur, and detailed high-quality data are obtained under closely controlled conditions. Separate effect tests cover a spectrum of tests from the most fundamental, to those investigating interactions between phenomena and hardware in a specific region of a physical system.

In the following paragraphs, brief descriptions of the separate effect tests considered by the PWR and BWR LOCA PIRT panel are provided. References to Appendix E, where additional summary information is found, are also provided.

<u>Cladding Mechanical Properties Tests (United States)</u>

Argonne National Laboratory (ANL) and the Pennsylvania State University (PSU) are working together on a NRC-funded program to investigate cladding properties at high burnups. Mechanical-properties testing is being done under both LOCA conditions and reactivity accident conditions. The objectives of the tests at relatively low temperatures and high strain rates appropriate for reactivity accident conditions are two-fold: to understand the degradation in cladding failure behavior at high burnup and to obtain stress-strain relationships that will serve as inputs to codes. A ring tensile specimen design has been developed and tested at ANL to generate tensile properties in the hoop direction. A related ring specimen design was developed and tested at PSU to provide a near plane-strain stress state that approximates the stress state produced by expanding fuel pellets during a reactivity accident. Similar testing will be done on axial tensile specimens electromachined from de-fueled portions of irradiated fuel rods and from unirradiated tubing specimens. These tests will be performed over the same temperature range and strain-rate range as the ring-stretch tests mentioned above. Biaxial tube burst tests will be done in a more limited temperature range of 300-400°C, but they will explore the effects on deformation and failure of stress biaxiality ratios from 1:1 to 2:1 at high strain rate.

LOCA Criteria Tests (United States)

The primary purpose of these tests is to evaluate the performance of high burnup fuel relative to the NRC cladding embrittlement criteria defined in 10CFR50.46. Within the Argonne National Laboratory test plan, the LOCA-criteria tests will be conducted on fuel rod segments (300 mm long) with the as-irradiated cladding outside- and inside-diameter oxide layers and the fuel intact. In this way, the high burnup effects of the oxide layers, the associated hydrogen pickup due to waterside corrosion, and the fuel cladding contact and/or bonding will be present in the tests. As the planned tests with high burnup fueled cladding are first-of-a-kind relative to previous tests that have been conducted, there are other important responses that will be studied to resolve the effects of high burnup operation on LOCA-relevant phenomena. For some tests, the temperature rise is sufficient to cause the cladding to balloon and burst. These tests will provide data on the circumferential magnitude and axial extent of the ballooning, the geometry of the burst, possible fuel particle relocation to the ballooned and burst region, and the effects of these phenomena on the circumferential and axial temperature profile. To the extent practical, these phenomena will be observed, described and quantified. In terms of post-test analyses, the equivalent cladding reacted (ECR), the phase distribution and the hydrogen content will be measured in the ballooned-and-burst region and either in the thermal-quench-failed region (if different from the ballooned-and-burst region) or in a non-ballooned, non-burst, non-failed axial location for the tests in which thermal-shock failure does not occur. The ECR values based on data will be compared to the calculated ECR values to determine the degree of conservatism associated with the models.

Cladding Mechanical Property Tests (Japan)

Ductility reduction due to hydrogen absorption and neutron irradiation was investigated for BWR cladding using the uniaxial tensile test many years ago, though both the hydrogen concentration and neutron fluence were much lower than the level currently of interest for high burnup fuels. Except for the general post-irradiation examination, BWR cladding has not been tested in recent years. Less significant corrosion and hydrogen pick-up than occurs in high burnup PWR fuel are an important factors is this situation. However, ductility reduction in BWR cladding is possible in the expected high-burnup range. Thus, mechanical property tests are planned. JAERI is interested in the morphology and the distribution of hydrides that are specific to BWR cladding. Tube burst tests for hydrided claddings are planned.

4.1.2. Integral Tests

Integral tests for high burnup fuel are experiments which investigate behavior in the fuel rod exposed to conditions simulating the environment that would be experienced in a reactor core undergoing the given transient.

In the following paragraphs, brief descriptions of the integral tests considered by the PWR and BWR LOCA PIRT panel are provided. References to Appendix E, where additional summary information is found, are also provided.

BWR Transient Dryout and Rewet Tests (United States)

The power oscillations instability and the LOCA have been identified as key events for the evaluation of fuel performance for a BWR. In an instability event the BWR will be at low flow for natural circulation and experience power oscillations. During these oscillations, the high power fuel bundles may undergo periodic boiling transition and rewet following each power pulse. As long as the peak cladding temperature remains below the minimum film boiling temperature, rewet will occur and excessive fuel heat-up is avoided. However, if the cladding temperature exceeds the minimum film boiling temperature (approximately 600 °C (1100 °F)) following a power pulse, the fuel may not rewet and substantial fuel heat-up can occur. The prediction of transient dryout and rewet is essential for the evaluation of the fuel performance for a power oscillation event. Additional information on the BWR transient dryout and rewet tests is provided in Appendix E.

Dryout Effects on High Burnup Fuel (OECD Halden Reactor Project-Norway)

The objective of the dry-out test series was to provide information on the consequences for fuel of short-term dry-out incidents in a BWR. The experimental method employed was to expose fuel rod with different burnups to single or multiple dry-out events; to follow this by either unloading or continued operation in the reactor; and to finish with post irradiation examination and testing with emphasis on fuel clad properties. Additional information on the test series is provided in Appendix F-2.

4.2. Analytical Databases

The experimental data derived from the programs described in the previous section are valuable in their own right because they provide insights into the basic physical processes occurring in a reactor should high burnup fuel undergo a LOCA. The data play an equally if not more important role when applied to the validation of physical models of high burnup fuel behavior. Once physical models are developed that incorporate all the highly important processes and phenomena, incorporated in an integrated computer model, and validated, the resulting code can be used to predict the behavior of high burnup fuel in a reactor undergoing a LOCA.

The modeling features of three representative computer codes currently being developed, validated, and used to predict the behavior of high burnup fuel undergoing a reactivity transient were described in Appendix F of the PWR rod ejection PIRT report [4-1] and will not be repeated in this report. Each of the codes simulates the following aspects and their coupling: (1) fuel and clad mechanical behavior, (2) fission gas transient behavior, and (3) the thermal behavior of the system (fuel, gap, clad, and coolant).

The FRAPTRAN code is the NRC's single-rod fuel performance analysis program. It calculates the response of single-fuel rods to operational transients and hypothetical accidents. Features of the FRAPTRAN code are described in Ref. 4-1, Appendix G, Table G-2.

The FALCON code is a utility-sponsored finite-element-based best-estimate analysis program designed to compute the transient thermal and mechanical behavior of a light water reactor fuel rod during both normal and off-normal events. Features of the FALCON code are described in Ref. 4-1, Appendix G, Table G-1.

The SCANAIR code is a ISPN (France)-sponsored thermal-mechanical analysis program for modeling the behavior of PWR irradiated fuel rod during fast power transients. Features of the SCANAIR code are described in Ref. 4-1, Appendix G, Table G-3.

4.3. References

4-1. Higar, L. E. Hochreiter, S. Langenbuch, F. J. Moody, A. T. Motta, M. E. Nissley, J. Papin, K. L. Peddicord, G. Potts, D. W. Pruitt, J. Rashid, D. H. Risher, R. J. Rohrer, J. S. Tulenko, K. Valtonen, N. Waeckel, and W. Wiesenack, "Phenomenon Identification and Ranking Tables (PIRTs) for Rod Ejection Accidents in Pressurized Water Reactors Containing High Burnup Fuel," Los Alamos National Laboratory document LA-UR-99-6810, Rev. 3 (October 11, 2000).

4-2. B. E. Boyack, J. G. M. Andersen, C. A. Alexander, B. M. Dunn, T. Fuketa, L. E. Hochreiter, R. O. Montgomery, F. J. Moody, A. T. Motta, K. L. Peddicord, G. Potts, D. W. Pruitt, J. Rashid, R. J. Rohrer, J. S. Tulenko, K. Valtonen, and W. Wiesenack, "Phenomenon Identification and Ranking Tables (PIRTs) Power Oscillations Without Scram in Boiling Water Reactors Containing High Burnup Fuel," Los Alamos National Laboratory document LA-UR-00-3122, Rev. 2 (October 11, 2000).

ADDITIONAL PANEL INSIGHTS

Through the course of the PWR and BWR LOCA PIRT activity, the panel developed important insights. These insights are briefly summarized in this section.

5.1. Technical Insights

1. Descriptions of three transient fuel rod analysis codes, FRAPTRAN, FALCON, and SCANAIR were provided to the PIRT panel. In addition, the features and capabilities of each code were cross-correlated with a list of phenomena occurring in the fuel pellet, pellet-cladding gap, cladding, and coolant. The tabulated results provided an excellent yet concise overview of the modeling features of each code. These results are found in Ref. 5-1, Appendix F.

2. Very little data exist about the state of fuel at burnups approaching 75 GWd/t. Consequently, the PIRT applies most directly to burnups of 62 GWd/t. The panel did assess the applicability of its phenomenon importance rankings at 75 GWd/t and this information is tabulated in each of the PIRT tables in Section 3. In addition, the panel also addressed the question of what additional information is needed to justify increasing the burnup limit form 62 to 75 GWd/t. This information is provided in Ref. 5-1, Appendix H.

5.2. Procedural Insights

1. For a given PIRT effort, it is important that the phenomena list be defined and organized such that it benefits the users. For the present PIRT, the term phenomena was broadly defined to include phenomena, processes, conditions, properties, and code- and experiment-related factors in two code-focused categories and two experimental-focused categories. Although this definition was much broader than previous PIRT development efforts, it served the purpose of identifying and ranking items germane to the needs of the participants.

2. The most useful primary evaluation criteria were found to be those that are not only physically based but also are most closely and directly linked to the phenomena that have been identified and are being ranked. Hence, somewhat more conservative criteria related to fuel damage were used rather than loss of core coolability.

3. It was vitally important that the panel had clear and agreed-upon phenomena definitions in place before ranking discussions were held. Having access to commonly held definitions ensures that each individual panel member and the collective panel is assessing importance from a common foundation. These definitions are given in Appendices A-D.

4. The panel reached a common understanding of the rationale to be used in assessing importance before proceeding with the ranking effort. These rationales are given in Appendices A-D.

5. Various phenomena are linked in a cause-effect relationship. The question arose whether a panel should consider the importance of each phenomenon individually or within the concept of linkages. The panel decided that the best approach was to treat each phenomenon individually.

6. Exposure to experimental data, if available, was highly desirable. The value of this exposure is enhanced if presented by those with a high level of technical expertise related to the data. Therefore, expert tutorials were presented to the panel and these tutorials are given in Appendices _ - _.

7. Exposure to code-calculated results, if available, was also highly desirable, assuming that the adequacy, limitations, and applicability of the code were also presented. The value of this exposure is enhanced if presented by those with a high level of technical expertise related to the code, code-calculated results, and adequacy and applicability of the code. Such presentations were included in the tutorials.

8. As various rationales were recorded, significantly different and contradictory rationales were sometimes expressed. These differences were not immediately explored due to time constraints. However, for those phenomena that became candidates for significant expenditures of effort or resources, these differing viewpoints were revisited.

9. Written ballots are a less-effective means of collecting information from panel members than real-time voting at panel meetings. The reason is that panel members do not have the benefit of hearing and addressing as a group the logical basis for each issue. Therefore, most of the voting was done during panel meetings.

10. The recording and extraction of rationales from the meeting transcript proved to be a workable but difficult procedure. The oral rationales were often provided as urged by the meeting facilitator in response to an effort to complete agenda items. Because of the size of the PIRT panel, insufficient time was spent developing a better joint understanding of a number of the stated rationales.

11. Breakout groups proved to be an effective approach to improving the PIRT findings. The breakout groups were smaller and consisted of panel members having expertise in the portions of the document being reviewed. The smaller groups provided the panel members a better forum for expressing their opinions. The use of breakout (working) groups on subsequent large-panel PIRT efforts is highly recommended.

12. A refinement of the PIRT process by which the panel explicitly addresses the frequency of occurrence of a particular phenomenon is needed. On occasion, the panel knew that a particular process or phenomenon was highly unlikely. This knowledge appears to have been reflected in the importance vote on occasion.

References

5-1. B. E. Boyack, C. A. Alexander, R. C. Deveney, B. M. Dunn, T. Fuketa, K. E. Higar, L. E. Hochreiter, S. Langenbuch, F. J. Moody, A. T. Motta, M. E. Nissley, J. Papin, K. L. Peddicord, G. Potts, D. W. Pruitt, J. Rashid, D. H. Risher, R. J. Rohrer, J. S. Tulenko, K. Valtonen, N. Waeckel, and W. Wiesenack, "Phenomenon Identification and Ranking Tables (PIRTs) for Rod Ejection Accidents in Pressurized Water Reactors Containing High Burnup Fuel," Los Alamos National Laboratory document LA-UR-99-6810, Rev. 3 (October 11, 2000).

APPENDIX A

CATEGORY A
PLANT TRANSIENT ANALYSIS

PHENOMENA DESCRIPTIONS AND RATIONALES FOR IMPORTANCE RANKING, APPLICABILITY, AND UNCERTAINTY

This appendix provides a description for each phenomenon appearing in Table 3-1, Plant Transient Analysis PIRT. Entries in the Table A-1, columns 1 and 2, follow the same order as in Table 3-1. Table A-1, column 3, also documents the PIRT-panel developed rationales for three types of Panel findings.

First, rationales are provided for the importance (High, Medium, or Low) assigned by the panel to each phenomenon. Because importance ranking was established by a vote of the panel members, a rationale is provided whenever one or more panel members voted a particular rank, i.e., High, Medium or Low. If there were no votes for a given importance rank, "No votes" is entered.

Second, the PIRT panel considered the applicability of the baseline PIRT to a broader set of circumstances, e.g., different fuel arrays, cladding types, reactor types, and burnups to 75 GWd/t. The specific question addressed by the PIRT panel was as follows: "Could the importance ranking assigned for the given phenomenon in the baseline PIRT be for different for other fuel arrays, cladding types, reactor types, or burnups?" If this question is answered with a "no", the following entry appears in Table C-1: "Baseline PIRT importance rank is applicable." If this question is answered with a "yes", the rationale is entered. Additional details are presented in the footnotes to Table 3-1.

Third, the PIRT panel considered the current state of knowledge or uncertainty regarding each phenomenon. The phenomenon is characterized as "known (K)" if approximately 75-100% of full knowledge and understanding of the phenomenon exists. The phenomenon is characterized as "partially known (PK)" if between 25-75% of full knowledge and understanding of the phenomenon exists. The phenomenon is characterized as "unknown (UK)"if less than 25% of full knowledge and understanding of the phenomenon exists. Because the uncertainty ranking was established by a vote of the panel members, a rationale is provided whenever one or more panel members voted a particular uncertainty, i.e., known, partially known, or unknown. If there were no votes for a given uncertainty level, "No votes" is entered.

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Gap size	Distance between pellet outside and inside clad diameters. H(7) Affects the rate of energy release from the fuel. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): There is a lot of in-pile data available and the data reveals that the gap is closed or nearly closed for high burnup. PK(0): No votes UK(0): No votes
Initial conditions	Gas pressure	Pressure of the gas in the rod. H(7) Sets the initial conditions for response of the cladding and can affect clad conductance. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Cumulative fission gas release is not well known. UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Gas composition	Composition of the gas in the rod (mole fractions of the fill and fission gas components). H(1) Affects gap heat transfer coefficient and heat release from fuel. M(6) Solid contact is majority of gap conductance. L(0) No votes Fuel: Y Rationale???????????? Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Large uncertainty in composition at higher burnup. UK(0): No votes
Initial conditions	Pellet and cladding dimensions	Characteristic physical dimensions, as a function of burnup. H(0) No votes M(7) Assumes that we have separated the pellet and clad dimensions from the gap and the dimensions are well known. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Design values are well controlled and can be predicted with acceptable accuracy. PK(0): No votes UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Burnup distribution	Radial and axial burnup magnitude and distribution in the core. H(7) Determines the power distribution and fuel conditions at initiation of the accident. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Known from the calculations during the fuel cycle. PK(0): No votes UK(0): No votes
Initial conditions	Cladding oxidation (ID & OD)	The amount of prior zirconium oxide on both the inside and outside cladding surfaces. H(0) No votes M(0) No votes L(7) Does not affect the overall system response. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Large uncertainty in the amount and structure of the oxide at high burnup. UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Coolant conditions	Thermal-hydraulic conditions in the core including pressure, temperature, quality, void fraction, and mass flow rate. H(7) Has a significant impact on determining the outcome of the transient. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Well known and characterized for a plant. PK(0): No votes UK(0): No votes
Initial conditions	Rod free volume	The plenum and other free volumes within the fuel rod occupied by the gas. H(7) Can affect fuel rod burst and blockage as well as the timing of the blockage. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Larger scatter in the data reflecting the effect of the gap moving into the cracks in the pellet. UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Gas communication (full)	The ability of the gas in the free volume to move axially within the fuel rods, thereby providing uniform gas pressure. H(0) No votes M(2) No communication would lead to very high local pressures. L(5) Time scale of accident is sufficient long to allow communication. Fuel: N Clad: N Reactor: N Burnup: Y – higher burnup can cause fuel-clad bonding which could decrease resistance to heat transfer. K(0): No votes PK(7): Large uncertainty, but some data are available. UK(0): No votes
Initial conditions	Gadolinium distribution (conductivity effect)	The spatial distribution of gadolinium within the core, which affects the thermal conductivity of the fuel rods. H(0) No votes M(0) No votes L(7) Small effect on conductivity, which has a smaller effect on system response. Fuel: N Clad: N Reactor: N Burnup: N K(7): Known accurately from calculations. PK(0): No votes UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Initial stored energy-fuel	The total energy content of the fuel rods at initial power conditions before the LOCA. H(7) Determines fluid conditions that lead to the peak cladding temperature during blowdown; also affects reflood. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Known from calculations. PK(0): No votes UK(0): No votes
Initial conditions	Initial stored energy-structure	The total energy content of structures within the vessel at initial power conditions before the LOCA. H(7) Can affect the heat release to the coolant, particularly for small LOCA and large LOCA at low pressure. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Known from plant calculations. PK(0): No votes UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Initial core pressure drop (grids)	The initial axially varying pressure within the core. H(0) No votes M(0) No votes L(7) Does not have a significant effect on the transient as an initial condition. Fuel: N Clad: N Reactor: N Burnup: N K(7): Known from data. PK(0): No votes UK(0): No votes
Initial conditions	Pellet radial power distribution	The radial distribution of the power produced in the fuel rods. H(0) No votes M(0) No votes L(7) Distribution of energy within fuel is not important; amount of energy is important. Fuel: N Clad: N Reactor: N Burnup: N K(7): Known from calculations for fuel pins. PK(0): No votes UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Rod axial power distribution	The magnitude and axial distribution of the power produced in the fuel rod. H(7) Has a significant impact on the peak cladding temperature as it affects the location of the peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Known from plant analysis calculations. PK(0): No votes UK(0): No votes
Initial conditions	Fuel assembly peaking factors	A fuel assembly's power compared to the core average (radial peaking factor). H(7) Has significant effect on peak cladding temperature, and allowable KW/foot determines the hot assembly average rod. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Design parameter is well known. PK(0): No votes UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Pin peaking factors Note: for codes in which the detached rod model is combined with the thermal-hydraulic code, e.g., BWR TRAC, this factor is more important.	Pin power distribution within an assembly. H(0) No votes M(1) Important for rod-to-rod radiation for BWR. L(6) Not important for hydraulic calculation for the system. Fuel: N Clad: N Reactor: Y – ranked higher for BWRs. Burnup: N K(7): Design parameter is well known. PK(0): No votes UK(0): No votes
Initial conditions	Fuel cycle design	H(7) Determines the reactor power distribution and burnup. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): This is a result of the design process and well known; it can be accurately calculated given the plant state. PK(0): No votes UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient power distribution	Moderator feedback	Reactivity feedback from moderator density and density changes in active channels. These changes are a result of direct deposition to the coolant and heat transfer from the cladding. H(7) Shuts down the plant due to voids for LBLOCAs in PWRs and BWRs. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Can be accurately calculated given the plant state. PK(0): No votes UK(0): No votes
Transient power distribution	Decay heat power	The power produced due to decay reactions of actinides and fission products. H(7) This is the significant heat source to be considered because 97-99% of the energy is deposited in the fuel. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Accurately known from tests. PK(0): No votes UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient power distribution	Fuel temperature feedback	Reactivity feedback from fuel temperature changes. This effect results from the heating of the fuel and associated neutronic effects, in particular the Doppler effect, and heat transfer from the fuel rod cladding. H(0) No votes M(0) No votes L(7) Not significant as compared to the void coefficient, which shuts down the plant. Fuel: N Clad: N Reactor: N Burnup: N K(7): Known well from temperature distribution. PK(0): No votes UK(0): No votes
Transient power distribution	Delayed neutron fraction	The fraction of fission neutrons that are not emitted instantaneously, designated beta (β). H(0) No votes M(0) No votes L(7) Not a significant contributor to core power for a LOCA. Fuel: N Clad: N Reactor: N Burnup: N K(7): Known from core physics. PK(0): No votes UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient power distribution	Fractional energy deposition in moderator and structures	The fraction of total fission and decay energy that is deposited directly in the coolant and the structures. H(0) No votes M(0) No votes L(7) Very small fraction (1% - 2.6%) is deposited outside of the fuel in other structures. Fuel: N Clad: N Reactor: Y – a BWR has more structures and thus, the phenomenon could be more important. Burnup: N K(7): Can be accurately calculated. PK(0): No votes UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood, and core spray heat transfer)	Single phase convection	Heat transfer from fuel outer surface to adjacent single-phase liquid or vapor. H(7) Primary heat transfer mode for small-break LOCA and also for large-break LOCA for dispersed flow film boiling. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Well known, ample data. PK(0): No votes UK(0): No votes
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood, and core spray heat transfer)	Subcooled boiling, nucleate boiling, bulk boiling, and forced convection vaporization	Heat transfer to adjacent liquid resulting in the formation of vapor at nucleation sites on the cladding surface or in the bulk liquid. H(7) Significant heat transfer mechanism for covered regions for small breaks in BWRs as well as during a PWR reflood. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Well known, ample data. PK(0): No votes UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood, and core spray heat transfer)	Critical heat flux/dryout	The heat flux that causes vaporization sufficient to prevent liquid from arriving at the heated surface. H(7) Affects the timing of DNB/dryout and the resulting peak cladding temperature. M(0) No votes L(0) No votes Fuel: Y – Fuel-assembly design-type dependent. Clad: N Reactor: N Burnup: N K(7): Well known, can predict with sufficient accuracy. PK(0): No votes UK(0): No votes
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood, and core spray heat transfer)	Film boiling over a wide void fraction (inverted annular, dispersed flow)	Heat transfer from the cladding outer surface through an adjacent vapor film to the liquid at a rate sufficient to prevent direct liquid to cladding contact. H(7) This is the regime in which the peak cladding temperature occurs. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): No fundamental models exist and there is a lot of scatter in the data. UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood, and core spray heat transfer)	Radiation heat transfer to coolant	Radiative thermal energy transport to the surrounding vapor/liquid environment. H(0) No votes M(0) No votes L(7) Not a significant effect for the transient analysis calculations. Fuel: N Clad: N Reactor: N Burnup: N K(7): This is a well-known phenomenon. PK(0): No votes UK(0): No votes
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood, and core spray heat transfer)	Rewet	Heat transfer occurring from liquid contact with the cladding surface after dryout; occurs when the surface temperature has decreased to the minimum film boiling point. H(7) Determines the boundary conditions for either good or bad cooling. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Large uncertainty in the models that exist. All models will predict rewet, but the timing could be off significantly. The uncertainty is toward the lower end of the PK range. UK(0): No votes

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood, and core spray heat transfer)	Rod to spacer-grid thermal-hydraulic interaction	The enhanced convective heat transfer effects downstream of the spacer grids due to mixing and flow redistribution for single- or two-phase flows. H(6) Can significantly affect peak cladding temperature, ballooning shape, and distribution. M(1) Lower order effect compared to the more dominant heat transfer modes. L(0) No votes Fuel: Y – Fuel assembly type dependent. Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Lots of scatter in data; no really good models, the uncertainty is towards the lower end of the PK range. UK(0): No votes

DRAFT

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood, and core spray heat transfer)	Spacer grid rewetting and droplet breakup	The wetting of spacer grids, which enhances the interfacial heat transfer at and downstream of the spacer grids. H(7) Has a significant effect on the vapor temperature, which directly affects the peak cladding temperature. M(0) No votes L(0) No votes Fuel: Y – Fuel assembly design directly affects this phenomenon. Clad: N Reactor: N Burnup: N K(0): No votes PK(0): No votes UK(7): Insufficient data to develop models to predict phenomenon.
Transient coolant conditions as a function of elevation and time	Temperature	Temperatures of the gas and liquid phases of coolant flowing along the fuel rod. H(7) Determines the local heat transfer coefficient sink temperature and resulting peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): For two-phase conditions, the degree of non-equilibrium is not well known. UK(0): No votes

DRAFT

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient coolant conditions as a function of elevation and time	Flow rate/directions (CCFL)	Flow rate and direction of gas and liquid phases flowing along the fuel rod (including crossflow and counter current flow limiting effects). H(7) Determines the local heat transfer and resulting peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Accurate predictions of the local two-phase flow behavior is difficult. UK(0): No votes
Transient coolant conditions as a function of elevation and time	Quality	The mass flow fraction of steam (gas) in the two-phase mixture flowing along the fuel rod. H(7) Determines the local heat transfer and resulting peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Accurate predictions of the local two-phase flow behavior is difficult. UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient coolant conditions as a function of elevation and time	Void fraction	The volume fraction of steam (gas) in the two-phase mixture. H(7) Determines the local heat transfer and resulting peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Accurate predictions of the local two-phase flow behavior is difficult. UK(0): No votes
Transient coolant conditions as a function of elevation and time	Pressure	The absolute total pressure in the coolant channel along the rod. H(7) Affects the coolant properties, which in turn determine the heat transfer, emergency core cooling flows, high-pressure safety injection, etc. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Effects are well known. PK(0): No votes UK(0): No votes

DRAFT

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient coolant conditions as a function of elevation and time	Partial vapor pressure	The partial steam pressure in the coolant channel along the rod. H(0) No votes M(0) No votes L(7) Not expected to be an important phenomenon in the core. Fuel: N Clad: N Reactor: N Burnup: N K(7): Assumes that non-condensable concentrations in the coolant due to fuel failure are known. PK(0): No votes UK(0): No votes
Transient coolant conditions as a function of elevation and time	Cross flow effects due to flow blockage	The extent to which axial flow along the rod is diverted from the associated fuel subchannel due to pressure gradients and deformation of the rods. H(7) Affects the flow in the hot assembly, which directly impacts the calculated peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): At the low end of PK due to the limited amount of data available. UK(0): No votes

DRAFT

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Plastic deformation of cladding (thinning, ballooning and burst)	Irreversible changes in cladding dimensions caused by pressure differentials or mechanical loadings at high temperatures. If cladding burst occurs, the final plastic deformation at the burst location is characterized by the burst strain. H(5) This model is needed to predict the flow blockage. M(0) No votes L(0) No votes Fuel: N Clad: Y – Model needs to be specific to the cladding type. Reactor: N Burnup: N K(5): A large amount of data and modeling experience exists to support this vote. Material model is affected by high burnup but this is addressed as a separate item. PK(0): No votes UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Direct gas pressure loading	The combination of available fission gas combined with the fill gas in determining an internal pressurization. H(5) This defines the loading mechanism that drives the cladding deformation. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(3): Based upon the validity of the perfect gas law used in the system code. PK(2): Large uncertainty in the prediction of gas release for a given burnup. UK(0): No votes
Fuel rod response	Thermal deformation of pellet and cladding	Reversible changes in pellet and cladding dimensions caused by thermal expansion. H(0) No votes M(0) No votes L(5) This is a second order effect. Fuel: N Clad: N Reactor: N Burnup: N K(5): Easy to calculate accurately. PK(0): No votes UK(0): No votes

DRAFT

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Elastic deformation of cladding	Reversible changes in cladding dimensions caused by pressure differentials or mechanical loadings. H(0) No votes M(3) This calculation determines the initial conditions for a plastic deformation calculation. L(2) Second order effect compared to the plastic deformation. Fuel: N Clad: N Reactor: N Burnup: N K(5): Easy to calculate accurately; textbook basis. PK(0): No votes UK(0): No votes

DRAFT

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Heat resistances in fuel, gap, cladding, and oxide	The resistances offered by the fuel, gap, and cladding to the flow of thermal energy from regions of high temperature to regions of lower temperature. The resistance is dependent upon path length and thermal conductivity, which change with burnup and other processes, e.g., the buildup of oxide on the cladding surfaces. H(5) This governs the thermal response that determines the energy release to the coolant. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Modeling method is well known. PK(1): Large scatter in data; depends on power history, pellet cracking, etc. UK(0): No votes

DRAFT

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Axial and radial temperature distributions	Axial and radial temperature distributions, as used to determine pellet properties and gas temperatures. H(5) This determines the heat from the fuel to the coolant. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Not recorded. ?????????????????????????????????????? PK(1): Depends on model and associated accuracy. UK(0): No votes
Fuel rod response	Metal-water reaction heat addition	The additional heat generated in the cladding due to metal-water reactions. H(0) No votes M(1) Depends on temperature level. L(5) The heat addition to the system calculation due to metal-water reaction is a very small component of the total heat transport. Fuel: N Clad: N Reactor: N Burnup: N K(5): Available models are sufficiently accurate. PK(0): No votes UK(0): No votes

DRAFT

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Cladding oxidation magnitude (ID/OD)	Thickness of oxide layers on inner and outer surfaces of cladding. H(0) No votes M(0) No votes L(5) Not important for a system code. Fuel: N Clad: N Reactor: N Burnup: N K(4): This can be calculated with adequate accuracy. PK(1): Temperature is not calculated with adequate accuracy. UK(0): No votes
Fuel rod response	Cladding temperature	The cladding thermal state (temperature) as used in determining cladding properties and leading to cladding deformation. H(5) Significant for determining key response such as flow blockage and heat flow to the coolant. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(3): Assuming that plant and boundary conditions are known, we can calculate cladding temperature to within 30%. PK(2): Boundary conditions are not well known. UK(0): No votes

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Burst criteria	Combinations of physical parameters, which are expected to cause cladding, burst. For example, NUREG-0630 correlates burst temperature as a function of engineering hoop stress and heatup rate. H(5) Can be the source of substantial flow blockage. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Outdated data; corelations require signification improvement, particularly at high burnup where the hydrogen dependency must be better characterized. UK(0): No votes

DRAFT

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Cladding phase changes	Change in the cladding microstructure from alpha phase (low temperature) to the alpha + beta phase, to beta phase (high temperature). The phase change energy of transformation can effectively increase the cladding specific heat over the transition temperature range. The phase change affects ductility resulting in significant effects of plastic deformation (creep rate and burst). Changes in cladding alloy or hydrogen content affect the transition temperature changes. H(0) No votes M(4) Affects the thermal/mechanical properties. L(1) Second-order element. Fuel: N Clad: N Reactor: N Burnup: N K(5): Phase changes are well known. PK(0): No votes UK(0): No votes

DRAFT

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Time of burst	The amount of time elapsed between initiation of the LOCA and the predicted cladding burst. H(1) Burst time directly affects peak cladding temperature. M(4) Causes significant flow blockages. L(1) Second order effect. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Factors influencing or determining the time of burst are not well known. UK(0): No votes
Fuel rod response	Location of burst and blockage	The axial position at which cladding burst and flow blockage occur. H(5) Supplies the boundary conditions for the rod calculation. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Given the power shape, the location can be determined with adequate accuracy. PK(2): Some factors in determining the location have uncertainties. Grid effects affect burst location and the amount of blockage. UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Fuel relocation	Movement of pellet fragments into a region where cladding plastic deformation (ballooning or burst) has occurred. Fuel relocation changes the local linear heat rate and affects gap conductance and fuel thermal resistance. H(0) No votes M(2) Could have an impact on the parameters to be calculated (low medium stated) L(4) Small local effect on system analysis. Could make the calculation burst node limiting. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(0): No votes UK(5): Limited data available.

DRAFT

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Time dependent gap-size heat transfer	The gap size is a result of plastic, thermal, and elastic deformation. The heat transfer across the gap is a function of gap size, conductance of the gas mixture, and the temperatures of the pellet outside diameter and cladding inside diameter (radiative heat transfer).; H(5) Primary heat transfer path for transporting heat from the fuel to the coolant. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(1): Approach to calculation of gap conductance is well known, given the input parameters. PK(5): Overall heat transfer coefficient for gap is well known but the gap size is not well known. UK(0): No votes

DRAFT

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Thermal and mechanical properties of pellet and cladding	The thermal and mechanical properties of the pellet and cladding, e.g., heat capacity, conductivity, yield stress, and creep, are needed to calculate the temperature and deformation response of the fuel rod. H(5) Governs the thermal and mechanical response of the pellet and cladding. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): A large database exists but there are incomplete data at higher burnup and temperature ranges. PK(0): No votes UK(0): No votes

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Multiple rod mechanical effects	Rod-to-rod mechanical interactions	Interaction between two or more rods, including guide tubes, water rods, and channels. Occurs when one or all rods are deformed due to swelling or bowing, including mechanical contact and conduction heat transfer., such that the rods are in physical contact. H(0) No votes M(1) Depends on the number of rods, how close they are, and if they can cause local blockage. L(4) Local effect has a secondary impact on system transient. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(0): No votes UK(4): Not recorded?????????????????????????????????????
Multiple rod mechanical effects	Rod bow between spacer grids	Bowing of a fuel rod due to axially constrained thermal expansion. H(0) No votes M(0) No votes L(4) Local effect; not important for system response. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(0): No votes UK(4): Not recorded?????????????????????????????????????

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Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Multiple rod thermal effects	Rod-to-rod radiative heat transfer	Thermal radiation heat transfer between fuel rods. H(0) No votes M(0) No votes L(4) Important for hot-rod but not for system performance. Fuel: N Clad: N Reactor: Y – This is a dominant phenomenon for BWR bundle temperature calculations. Burnup: N K(4): Given the temperature distribution, the radiation heat transfer is well known. PK(0): No votes UK(0): No votes
Multiple rod thermal effects	Rod-to-channel box radiative heat transfer	Thermal radiation heat transfer between a fuel rod and the channel box in a BWR. H(4) Very important heat transfer mechanism for determining the MAPHGR limit in BWRs M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: NA Burnup: N K(4): Given the temperature distribution, the radiation heat transfer is well known. PK(0): No votes UK(0): No votes

DRAFT

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Multiple rod thermal effects	Rod-to-spacer grid local heat transfer	Heat transfer between a fuel rod and a spacer grid due to thermal radiation and conduction heat transfer. H(1) Directly affects heat transfer on the cladding which determines the blockage location and the degree of co-planar blockage. M(4) Grid affects rewet of fuel rod; contributes to heat transport from fuel. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(4): Data is available to indicate the grid temperature during LOCA conditions. UK(0): No votes
Multiple rod thermal effects	Rod-to-guide tube radiative heat transfer	Thermal radiation heat transfer between a fuel rod and a guide tube (PWR). H(0) No votes M(0) No votes L(4) Local effect; more important for hot rod peak cladding temperature calculation. Fuel: N Clad: N Reactor: NA Burnup: N K(4): Data is available to indicate the temperature during LOCA conditions. PK(1): Guide tubes are usually not modeled. UK(0): No votes

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Multiple rod thermal effects	Rod-to-water rod radiative heat transfer	Thermal radiation heat transfer between a fuel rod and a water rod (BWR). H(4) Important heat sink during spray cooling; more important for hot rod peak cladding temperature calculation. M(1) Second order effect. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Data is available to indicate the temperature during LOCA conditions. PK(0): No votes UK(0): No votes
Multiple rod thermal effects	Rod-to-inner channel radiative heat transfer	Thermal radiation heat transfer between a fuel rod and the inner channel box (BWR). H(4) Important heat sink during spray cooling; more important for hot rod peak cladding temperature calculation. M(1) Second order effect. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Data is available to indicate the temperature during LOCA conditions. PK(0): No votes UK(0): No votes

DRAFT

Table A-1
PWR and BWR LOCA Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)

APPENDIX B

CATEGORY B
INTEGRAL TESTING

PHENOMENA DESCRIPTIONS AND RATIONALES FOR IMPORTANCE RANKING, APPLICABILITY, AND UNCERTAINTY

This appendix provides a description for each phenomenon appearing in Table 3-2, Integral Testing PIRT. Entries in the Table B-1, columns 1 and 2, follow the same order as in Table 3-2. Tables B-1, column 3, also documents the PIRT-panel developed rationales for three types of Panel findings.

First, rationales are provided for the importance (High, Medium, or Low) assigned by the panel to each phenomenon. Because importance ranking was established by a vote of the panel members, a rationale is provided whenever one or more panel members voted a particular rank, i.e., High, Medium or Low. If there were no votes for a given importance rank, "No votes" is entered.

Second, the PIRT panel considered the applicability of the baseline PIRT to a broader set of circumstances, e.g., different fuel arrays, cladding types, reactor types, and burnups to 75 GWd/t. The specific question addressed by the PIRT panel was as follows: "Could the importance ranking assigned for the given phenomenon in the baseline PIRT be for different for other fuel arrays, cladding types, reactor types, or burnups?" If this question is answered with a "no", the following entry appears in Table B-1: "Baseline PIRT importance rank is applicable." If this question is answered with a "yes", the rationale is entered. Additional details are presented in the footnotes to Table 3-2.

Third, the PIRT panel considered the current state of knowledge or uncertainty regarding each phenomenon. The phenomenon is characterized as "known (K)" if approximately 75-100% of full knowledge and understanding of the phenomenon exists. The phenomenon is characterized as "partially known (PK)" if between 25-75% of full knowledge and understanding of the phenomenon exists. The phenomenon is characterized as "unknown (UK)"if less than 25% of full knowledge and understanding of the phenomenon exists. Because the uncertainty ranking was established by a vote of the panel members, a rationale is provided whenever one or more panel members voted a particular uncertainty, i.e., known, partially known, or unknown. If there were no votes for a given uncertainty level, "No votes" is entered

There were several phenomena for which no importance rank was recorded. In such cases "No rationale recorded" is entered.

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Fuel Burnup	Amount of nuclear fuel that has been consumed in fuel pellets used in the test article in, for instance, Gwd/t. H(5) This is the focus of the test and a high burnup rod should be selected so as to facilitate discovery of phenomena not yet recognized and so that unknown effects are not overlooked. Fuel morphology (fragmentation, rim characteristics, bonding, etc.) is important. M(1) Burnup is not important per se, but individual physical effects such as oxidation or rod internal pressure are important. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(6): Data, judgement UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena		Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Fuel	PU agglomerates (MOX fuel only)	For the selected fuel rod containing MOX, the degree and type of agglomerates (clusters) of plutonium should be charactized, e.g., agglomerate size. H(1) May affect the amount of fine grain material after relocation M(0) No votes L(6) The presence of agglomerates are not considered to be important to LOCA outcome. Fuel: NA Clad: N Reactor: N Burnup: N K(6): Judgement PK(0): No votes UK(1): Judgement

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Fuel Duty cycle	For the selected fuel rod, the history of burnup accumulation should be known. H(0) No votes M(4) Operating history sets many parameters which can influence test results. May affect the fuel cracking and the cladding corrosion and hydrogen pickup. L(3) There is no unique duty and all must be covered in order to determine the rupture strain results. Fuel: N Clad: N Reactor: N Burnup: N K(4): Code, data PK(3): Code, data, judgement UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Fuel type (absorbers, additives)	Some fuel vendors have different kinds of burnable absorbers in the rod. Various absorbers and additives should be considered when selecting fuel rods for refabrication followed by testing. H(0) No votes M(3) Additives may cause an attack on the cladding that could have unknown effects on the experimental results. Gadolinium may affect rim size. L(4) There is no evidence that possible impacts exist. Fuel: NA Clad: N Reactor: N Burnup: N K(0): No votes PK(4): Data, Judgement UK(2): Judgement

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding: Pre-existing oxidation (thickness, type, uniformity f[θ])	Extent and characteristics of pre-existing clad oxidation. H(2) High levels of oxidation indicates hydrogen in the metal and a different morphology. The rate of high temperature oxidation will be affected by these. Also remaining unoxidized material is affected. Oxidation characteristics are less important than associated hydrogen pickup. However, unprototypical fabrication conditons may artificially enhance its impact. For example, oxide layer produced under gaseous mixture of noble gas and stam is dense and protective, while oxide layer produced under irradiation is defective and not protective). M(4) No barrier effect was observed in the French tests nor, possibly, in the Japanese tests. Azimuthal changes may occur. L(1) To date sufficient French and Japanese testing has been completed to show that this phenomenon is not important. Fuel: N Clad: N Reactor: N Burnup: N K(6): Data PK(1): Judgement UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding: Spalling	Peeling of the oxide layer (high or low amounts) from the cladding leaving the underlying material exposed to the coolant. Can lead to a local cold spot and hydride blister formation H(0) No votes M(3) The clad under a spalled region is of questionable quality because there is less protection to the cladding under a spalled region. May affect azimuthal burst due to hydrogen content. However, after alpha to beta transformation, hydrogen will be in solution in the beta phase. L(4) The amount of spalled material is small and hydrogen blisters will dissolve. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data, judgement PK(5): Judgement UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding: Total hydrogen	Total amount of hydrogen in the cladding. H(3) When solubility of oxygen in the beta phase of zirconium is high, the ability of the cladding to handle loads is diminished. The micro-structure of the beta phase and its brittleness is affected. Affects burst (alpha to beta phase transformation), oxygen solubility in the beta phase, and post-quench ductility. M(4) Available information suggests hydrogen is not affecting quench behavior but may effect post quench behavior. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Data (Japanese and French testing) PK(2): Data, Judgement UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding: Hydrogen distribution	Spatial distribution of the hydrogen, including local hydride formations in the cladding (hydride rim) and including hydride blisters. H(0) No votes M(1) May affect burst (alpha to beta transformation). However, after this transformation, hydrogen will be in solution in the beta phase. L(5) The preexisting hydrogen distribution will be erased by the temperature excursion. Fuel: N Clad: N Reactor: N Burnup: N K(5): Data, judgement PK(1): Data, judgement UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding: Surface conditions (crud)	The presence of nodular corrosion, delamination, crud, scratches, and other irregularities. H(0) No votes M(1) May affect thermal-hydraulic behavior. L(5) Crud is not a significant factor in heat transfer and may have a small effect on swelling and rupture. A rod with representative surface conditions should be tested. Fuel: N Clad: N Reactor: N Burnup: N K(5): Data, calculations, judgement PK(1): Data, judgement UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding: Fluence/radiation damage	Material damage caused by the time-integrated particle flux to which the cladding is exposed (Energy > 1.0 Mev, i.e., fast fluence). H(0) No votes M(1) At 62 GWd/t, the major factor is hydrogen pickup. The important at 75 GWd/t is uncertain. L(5) All radiation damage is annealed out during the temperature excursion. Fuel: N Clad: N Reactor: N Burnup: N K(5): Data, calculations, judgement PK(1): Data, judgement UK(0): No votes

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding: Initial residual deformation (hourglass, creepdown)	Dimension condition after irradiation. H(0) No votes M(2) Uncertainty exists about the effects on ballooning and burst of cladding and gas communication (includes combined fuel and cladding effects). L(4) Residual stresses are annealed out during the transient. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Data, calculations UK(1): Judgement
Fuel rod selection	Cladding: Chemical bonding	Bonding (adhesion) between fuel and cladding at high burnup H(1) May affect burst and timing of relocation. M(4) When the bond is strong, there may be an effect on ballooning and burst, clad temperature at burst, and thermal shock resistance. L(1) Cracking during cool down reduces the effect. Fuel: Y (1): MOX Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Judgement UK(1): Judgement

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding: As fabricated wall thickness	Self defined. H(3) The thinner the initial wall thickness, the thinner the ligament after reactor exposure and the thinner the beta phase, as shown by the JAERI data. May have a different stress. M(1) Although there may be a difference in behavior, there may not be an impact relative to the 17% oxidation criterion. L(0) No votes Fuel: N Clad: Y Reactor: N Burnup: N K(2): Data (Japanese), judgement PK(2): Judgement UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	CladdingAlloy type: Alloy composition Microstructure/2nd phase particle Initial cold work Liner/nonliner clad	Characteristics of a candidate cladding alloy to be considered and documented during the selection process, given the same oxidation characteristics. H(2) Swelling and rupture results for claddings differ for unirradiated claddings. If the annealing effect is valid, this should hold for irradiated claddings as well. May affect burst (beta-favoring and alpha-favoring additions) and also oxygen distribution and hydrogen pickup. M(4) There could be differences in behavior (swelling and rupture, oxidation rates, quench behavior and alpha to beta transformation) but these are likely to be small. L(1) Low impact on high temperature oxidation rate. No need for specific integral tests. Issues addressed through separate effect tests. Fuel: N Clad: NA Reactor: N Burnup: N K(0): No votes PK(4): Data UK(2): Judgement

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Plateau temperature (plus variations)	A LOCA simulation will consist of a time versus temperature profile which consists of (1) an initial heatup period, (2) a period during which the temperature will be nearly constant, (3) a period of relatively slow cooling, and (4) a quench. The plateau temperature corresponds to period (2) as defined above. H(7) Soluability of the oxide in the beta phase increases susceptibility to brittle fracture. Consideration should be given to verifying that high temperature is not the worst case (see BAW-10277). In-reactor LOCA transient may exhibit a first thermal peak that may anneal the cladding and affect the clad strain and burst behavior. May affect oxygen distribution and hydrogen pickup. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(3): Data, calculations PK(4): Data, judgement UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Temperature ramp	A LOCA simulation will consist of a time versus temperature profile which consists of (1) an initial heatup period, (2) a period during which the temperature will be nearly constant, (3) a period of relatively slow cooling, and (4) a quench. The temperature ramp corresponds to period (1) as defined above. H(2) Ramp will create different effects on phase change kinetics and other issues. Creep depends on the time-temperature history. Affects burst. M4) Ramp rates between 2 and 50 °C/s do not significantly affect strain results and will not affect oxidation. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Data PK(2): Data, judgement UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Time at temperature	A LOCA simulation will consist of a time versus temperature profile which consists of (1) an initial heatup period, (2) a period during which the temperature will be nearly constant, (3) a period of relatively slow cooling, and (4) a quench. This phenomenon is the time from the start to the end of phase 3. H7) Controls the amount of oxidation M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Data PK(0): No votes UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Cooldown/quench/rewet rate initiation: (Clad temperature level, mass flow rate, pump or gavity feed, quality, subcooling)	A LOCA simulation will consist of a time versus temperature profile which consists of (1) an initial heatup period, (2) a period during which the temperature will be nearly constant, (3) a period of relatively slow cooling, and (4) a quench. The cooldown/quench/rewet rate initiation corresponds to periods (3) and (4) as defined above. H(6) Transformation structure and the properties of the transform material depend on cooling rate. A representative cooling rate should be used. H. Chung has shown that slow cooled specimens exhibit higher quench and impact resistances than fast cooled specimens. M(1) Same as the rationale for high but the impact is not large. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(2): Data PK(5): Data, judgement UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Plenum volume	A volume incorporated into the test article to be representative of internal pressure, amount of gases available, accommodate fuel expansion, and avoid end-effect. H(1) Provides the driving force for ballooning, burst, and partly for relocation. M(5) Poor plenum design can affect outcome, e.g., internal pressure and ballooning, but these may not affect quench behavior. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(6): Data, judgement PK(1): Data, judgement UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Internal pressure	The total pressure in the test specimen gap at the start of in-reactor testing resulting from the introduction of the fill gas at the time the test specimen was prepared. H(2) The pressure should be representative of the LOCA if the test is to be prototypical. Provides the driving force for ballooning, burst, and partly for relocation. M(3) The gas pressure should be representative of the transient but its impact is moderate. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Data, judgement PK(2): Data, judgement UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Attachments	Any item, e.g., instrumentation, affixed to the test article. H(1) The potential for affecting the outcome of the test is high so care must be taken to properly design and utilize attachments. M(6) The risk of artificial behavior is high for swelling and rupture but it is unlikely that there will be any effect on oxidation. Impact to be reduced as much as possible by adequate technology. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Data PK(2): Data, judgement UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Temperature measurement	Self defined H(6) The temperature is needed to draw conclusions from the test and to correlate results, e.g., amount of oxidation and embrittlement. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(6): Data PK(1): Data, judgement UK(0): No votes
Conduct of test	Gas composition	The composition of the gas in the gap and the plenum resulting from the introduction of the fill gas at the time the test specimen was prepared. H(0) No votes M(1) For in pile tests, the impact is believed to be small. L(6) There is no interaction with gas composition; second order parameter. Fuel: N Clad: N Reactor: N Burnup: N K(7): Data PK(0): No votes UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Design test such that axial and azimuthal temperature gradients are known	Instrumentation would be provided to measure the temperature variation around the circumference of the test fuel rod at one or more axial levels. H3) Impact on burst strain is significant and is needed if the results are to be adequately understood. Affects burst in single fresh rod experiments with cold shroud; importance is reduced in experiments with heated shroud or in bundle experiments and also at low burnups. M(3) This is very difficult to do. There will be multiple gradients. The impact on ECR will not be large. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Data PK(2): Data, judgement UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Single rod versus bundle	The phenomenon is best expressed as a question, namely, is it possible to characterize the needed phenomena in a single rod test article or is it necessary to conduct some testing in a bundle? High votes mean that a bundle test is needed while Low means a single rod tests will suffice. The evaluation is based on the effect of high burnup considering the availability of single rod to bundle tests at low burnup. H(1) Some bundle testing is necessary for: (1) providing prototypical azimuthal temperature gradients, (2) providing radial constraints on ballooning development, and (3) avoiding non-prototypical fuel fragment escape from the balloon. M(3) A lot unknown interactions occur between rods, rods limit the strains of other rods. It would be well if they were better understood. L(3) Bundle effects can arise but it is not clear how large these effects are. This should be addressed in other types of experiments that can include rod bow. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(6): Data. judgement UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Fuel/nonfuel	The importance of having fuel in the cladding (fuel) or being able to test absent the fuel in the cladding (nonfuel). H6() Data from fueled rods will provide information on bonding and bowing of high burnup fuel M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(2): Data, judgement PK5): Judgement UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Water chemistry	The chemical characteristics of the coolant used in the test are to be well characterized, e.g., oxygen potential is to be known. H(0) No votes M(6) Deviation within a range of water chemistries will not be that significant or cause significant effects. L(1) Test data confirms that there is very little difference in results over a reasonable range of water conditions. Fuel: N Clad: N Reactor: N Burnup: N K(7): Data PK(0): No votes UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Coolant flow conditions	Pressure, temperature, flow rate, quality, etc. H(0) No votes M(3) Coolability affects the clad temperature, which affects strain, location and timing. The oxide is not affected. L(4) Flow affects clad temperature and that will be measured. Fuel: N Clad: N Reactor: N Burnup: N K(6): Data PK(1): Data UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Heating source (internal or external, type, electrical, radiant, neutronic)	Heating will vary depending upon test type. This phenomenon focuses on the nature of the heating and its prototypicality with the intent of determining the degree to which the heating method is prototypical or nonprototypical affects the conclusions that can be drawn from the test. H(3) Azimuthal temperature variations can be caused by the heat source and that may affect strain. The quenching process may be different with internal heating and heat capacities. M(4) Cladding temperature can be controlled to overcome the effect of the source on cladding parameters. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(6): Data and calculations PK(1): Data and judgement UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Specimen length	The appropriate length of the test article such that the data delivered from the test is useable. H(2) The length of anticipated test sections is sufficient to both rupture and pre-rupture strains. M(5) Assumes some intelligence on the part of the experimental team. Little concern that sample will be too short. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(6): Data and calculations PK(1): Data and judgement UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen constraints (grids, spacers, structures)	The degree to which mechanical setup used to hold the test article in place is prototypical H(7) Low temperature burst strains are affected by constraints. Japan has shown effects on brittle fracture. The constraints should be prototypical and avoid over constraining the sample. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Data (JAERI) and judgement PK(2): Data UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Temperature effects of fuel relocation	Change in local cladding due to relocation of internal heat source (pellets) H(3) May cause hot spots that change selling and rupture, oxidation, and brittleness results. M(3) Less important for high burnup fuel because of fuel and clad bonding. L(1) Second order effect. Fuel: Y (1): For MOX fuel, the temperature effect will be more important because of the larger fraction of fine grain material. Clad: N Reactor: N Burnup: N K(4): Calculations PK(3): Calculations UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Fuel stored energy	The fuel stored energy, which depends upon the fuel temperature, amount of fuel, and fuel physical properties, should be known. Of the above, the fuel temperature is the parameter that must be measured during the test. H(1) Possible effects of debonding of clad and fuel and heat capacity of fuel will make it difficult to quench. M(1) Same reason as for high but felt to be less important, even a 2^{nd} order effect. L(3) The temperatures are controlled during the test and that is the most important impact. Fuel: N Clad: N Reactor: N Burnup: N K(5): Calculations PK(2): Judgement UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	Online: Clad temperature f(z, t)	Measurement of the time-varying cladding temperature as a function of azimuthal and axial location. H(7) This is the most important parameter characterizing behavior and it should be measured to the extent possible. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Data PK(3): Data and judgement UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	Online: Fuel temperature f(z, t)	Measurement of the time-varying fuel temperature as a function of axial location. H(0) No votes M(4) Difficult to obtain but desirable data. It provides a sensibility check of the experiment. L(3) Clad temperature is monitored and controlled and will reflect fuel temperature. Fuel: N Clad: N Reactor: N Burnup: N K(4): Data and calculations PK(2): Data and judgement UK(1): Judgement

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	Online: Time of failure	The time resolution of test rod burst failure occurrence. H(6) This information is needed to interpret and understand the tests and relating them to correlations. M(1) If burst occurs within the anticipated range, it will not effect oxidation or quench behavior. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Data and calculations PK(2): Calculations and judgement UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	Online: Time of fuel relocation	The time resolution of the time of initial movement of fuel following either ballooning or test rod failure. H(2) Determines the time that more power is available to heat the clad. M(2) It is more important to know that material moves than when it moves. Movement in an electrically heat test would be much less important or significant than in a nuclear test. L(3) For this test, with known clad temperature, knowing when relocation occurs will not effect the results. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(6): Calculations UK(1): Judgement

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	Online: Fuel dispersal	Measurement of the movement of fuel particles out of the cladding and into the coolant during a burst. H(0) No votes M(5) Will not affect the test but may be important to understanding and setting regulations. In a single pin test will be overestimated. Needs to be quantified. L(2) No drive to expel fuel and there is no current data on this. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(3): Judgement UK(3): Judgement

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	Online: Internal pressure (value and axial communication)	The pressure at two axial locations within the fuel rod is sought to characterize the axial transport of gases. H(3) Needed for correlation to swell rupture correlations. M(3) Desirable but difficult to measure for axial communication of gases. L(1) No influence on tests being run. Only affects ballooning and burst to second order. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data and calculations PK(4): Judgement UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	Online: Hydrogen release/evolution	The release of hydrogen to the steam. H(0) No votes M(3) Provides a marker for the evolution of the oxide versus time and as a check on kinetics correlations. L(4) Errors in this measurement will be high and the measurement is not needed to verfy kinetics. Fuel: N Clad: N Reactor: N Burnup: N K(5): Data PK(2): Judgement UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	Online: Fission product release	Detection of the time at which fission gases escape from the fuel rod into the test channel. H(1) Good source for determining the onset of failure. M(4) Important to know but we only know about long-lived isotopes. L(2) It has nothing to do with outcomes and won't add to in-reactor understanding. Fuel: N Clad: N Reactor: N Burnup: N K(5): Data PK(0): No votes UK(2): Judgement
Parameters/variables	Online: Steam consumption	The measurement of steam consumption is equivalent to oxidation monitoring. H(2) This data can be used to determine the time rate of oxidation. M(1) This data can be used to check German information on ECR. L(4) Accuracy is bad; this parameter does not affect the outcome of the test. Fuel: N Clad: N Reactor: N Burnup: N K(4): Data and calculations PK(3): Judgement UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	Online: Strain measurement	Measurement of the time-dependent variation of clad hoop strain during the test. H(2) Will provide added data on creep and burst; strain away from the rupture is important for creating a bundle simulation. M(3) Useful to understand results but can be obtained from separate effect tests. L(2) Does not affect outcome and the data obtained from separate effect tests is much better. Fuel: N Clad: N Reactor: N Burnup: N K(4): Data PK(3): Data and judgement UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	PTE: ECR at failure location (burst and/or thermal shock)	Following the test, post irradiation examination (PTE) is performed on the fuel rod to determine the outcome of the test on various measurable features. Definition needed. H(7) ECR is key data needed to interpret the test results. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Data PK(2): Data and judgement UK(0): No votes
Parameters/variables	PTE: Remaining prior beta thickness	H(6) A critical item of data needed for test interpretation. M(1) Some what less a critical result; failure is more important. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Data PK(3): Data and judgement UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	PTE: Cladding strain	End state cladding strain. H(3) Can be cross-correlated to separate effect tests. M(4) Useful data but only as it provides confirmatory data for separate effect tets. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Data PK(2): Data and judgement UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena		Definition and Rationale (Importance, Applicability, and Uncertainty)	
Parameters/variables	PTE:	Fuel relocation, residual bonding and/or dispersal	The amount of fuel that moved during the test and the location to which it was moved or dispersed is determined.	
			H(7)	May be the only way to quantify a potentially significant effect.
			M(0)	No votes
			L(0)	No votes
			Fuel:	Y (1): Low temperature burst strains are affected by constraints. Japan has shown effects on brittle fracture. The constraints should be prototypical and avoid over constraining the sample?????????
			Clad:	N
			Reactor:	N
			Burnup:	N
			K(0):	No votes
			PK(3):	Calculations and judgement
			UK(2):	Judgement

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	PTE: Metallography (oxide thickness microstructure, prior beta, hydrides, and cladding thinning)	The end state of the listed parameters are measured. H(7) Needed to properly interpret the test. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Data and calculations PK(2): Data and judgement UK(0): No votes
Parameters/variables	PTE: Chemistry (Total beta hydrogen and oxygen content)	The listed end state parameters are measured. H(7) Needed to properly interpret the test. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Data and calculations PK(2): Data and judgement UK(0): No votes

DRAFT

Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	PTE: Oxide spallation and delamination during cooldown	The listed end state parameters are measured. H(0) No votes M(1) No rationale available L(6) Does not affect the outcome of the test. Phenomena are inconsequential. Fuel: N Clad: N Reactor: N Burnup: N K(3): Data PK(2): Judgement UK(0): No votes

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Table B-1
PWR and BWR LOCA Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	PTE: Fission gas distribution	The listed end state parameter is measured. H(0) No votes M(2) Releases in rim and MOX agglomerates could affect pressure or filling of balloon with fuel. L(4) Characterizes release but has no impact on the outcome of the test. Fuel: Y (1): Low temperature burst strains are affected by constraints. Japan has shown effects on brittle fracture. The constraints should be prototypical and avoid over constraining the sample???????????? Clad: N Reactor: N Burnup: N K(0): No votes PK(3): Data and judgement UK(0): No votes

APPENDIX C

CATEGORY C
TRANSIENT FUEL ROD ANALYSIS

PHENOMENA DESCRIPTIONS AND RATIONALES FOR IMPORTANCE RANKING, APPLICABILITY, AND UNCERTAINTY

This appendix provides a description for each phenomenon appearing in Table 3-4, Transient Fuel Rod Analysis PIRT. Entries in the Table C-1, columns 1 and 2, follow the same order as in Table 3-3. Table C-1, column 3, also documents the PIRT-panel developed rationales for three types of Panel findings.

First, rationales are provided for the importance (High, Medium, or Low) assigned by the panel to each phenomenon. Because importance ranking was established by a vote of the panel members, a rationale is provided whenever one or more panel members voted a particular rank, i.e., High, Medium or Low. If there were no votes for a given importance rank, "No votes" is entered.

Second, the PIRT panel considered the applicability of the baseline PIRT to a broader set of circumstances, e.g., different fuel arrays, cladding types, reactor types, and burnups to 75 GWd/t. The specific question addressed by the PIRT panel was as follows: "Could the importance ranking assigned for the given phenomenon in the baseline PIRT be for different for other fuel arrays, cladding types, reactor types, or burnups?" If this question is answered with a "no", the following entry appears in Table C-1: "Baseline PIRT importance rank is applicable." If this question is answered with a "yes", the rationale is entered. Additional details are presented in the footnotes to Table 3-4.

Third, the PIRT panel considered the current state of knowledge or uncertainty regarding each phenomenon. The phenomenon is characterized as "known (K)" if approximately 75-100% of full knowledge and understanding of the phenomenon exists. The phenomenon is characterized as "partially known (PK)" if between 25-75% of full knowledge and understanding of the phenomenon exists. The phenomenon is characterized as "unknown (UK)"if less than 25% of full knowledge and understanding of the phenomenon exists. Because the uncertainty ranking was established by a vote of the panel members, a rationale is provided whenever one or more panel members voted a particular uncertainty, i.e., known, partially known, or unknown. If there were no votes for a given uncertainty level, "No votes" is entered.

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Gap size	Distance between pellet outside and inside clad diameters. H(5) Affects the rate of energy release from the fuel. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): There is a lot of in-pile data available and the data reveals that the gap is closed or nearly closed for high burnup. PK(0): No votes UK(0): No votes
Initial conditions	Gas pressure	Pressure of the gas in the rod. H(6) Sets the initial conditions for response of the cladding and can affect clad conductance; also affects burst and blockage. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes. PK(5): Cumulative fission gas release is not well known. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Gas composition	Composition of the gas in the rod (mole fractions of the fill and fission gas components). H(5) This parameter contributes to establishing initial fuel stored energy. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Detailed gas release model can generate more accurate gas composition but the accuracy remains at 30%. UK(0): No votes
Initial conditions	Pellet and cladding dimensions	Characteristic physical dimensions, as a function of burnup. H(5) More important for hot rod calculation than for system calculation. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Design values are well controlled and can be predicted with acceptable accuracy. PK(0): No votes UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Burnup distribution	The radial and axial burnup magnitude and distribution in the fuel rod. H(5) Establishes peaking factors – very important. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Known from the calculations during the fuel cycle. PK(0): No votes UK(0): No votes
Initial conditions	Cladding oxidation (ID + OD)	The amount of prior zirconium oxide on both the inside and outside cladding surfaces. H(6) Thermal resistance effect – establishes starting point and can influence degree to which criteria are satisfied; also affects peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(2): For a single rod, initial oxide thickness can be calculated with adequate accuracy. PK(4): There is a moderate amount of uncertainty in oxidation over 60 GWd/t. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Hydrogen concentration	The average hydrogen concentration in the cladding specified as the initial condition. H(5) Establishes initial ductility of cladding. M(0) No votes L(1) Second order effect on peak cladding temperature. Fuel: N Clad: N Reactor: N Burnup: N K(2): Hydrogen concentration can be accurately calculated from the oxide thickness. PK(3): Same as rationale for K but less certain about accuracy. UK(0): No votes
Initial conditions	Hydrogen distribution	The local distribution of hydrogen in the cladding and hydride orientation specified as the initial condition. H(5) Establishes initial ductility of cladding. Not modeled in most codes at present time. M(0) No votes L(1) Second order effect on peak cladding temperature. Fuel: N Clad: N Reactor: N Burnup: N K(2): Hydrogen distribution can be directly correlated to the oxide thickness. PK(3): Same as rationale for K but less certain about accuracy. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Fast fluence	Time integrated fast neutron flux to which the cladding is exposed. H(5) Establishes cladding properties. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Effluence history is well known. PK(0): No votes UK(0): No votes
Initial conditions	Porosity distribution	The porosity distribution, including the rim, specified as the initial condition that is used to calculate the thermal conductivity and the fission gas transient behavior. H(5) Affects the conductivity of the pellet and the amount of fission gas release; affects the power distribution. M(0) No votes L(1) Second order effect on peak cladding temperature. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Sufficient data exist for 62 MWd/t but data are incomplete for higher burnups. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Rim size	Width of zone at outer periphery of pellet characterized by high porosity, high local burnup and plutonium content, and small grain structure containing fission gases in tiny closed pores specified as the initial condition. H(5) Affects radial power distribution and radial temperature distribution (stored energy) M(0) No votes L(1) Second order effect on peak cladding temperature. Fuel: Y: Rim size not as important for MOX fuel. Clad: N Reactor: N Burnup: N K(0): No votes PK(5): For the purpose of LOCA analysis, enough data exists to characterize the rim size adequately. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Pellet radial power distribution	The radial magnitude and distribution of the power produced within the fuel rod, including the effect of plutonium in the rim region. H(0) No votes M(5) Determines radial distribution of stored energy; not as important as axial distribution. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Can be calculated with adequate accuracy. PK(0): No votes UK(0): No votes
Initial conditions	Rod axial power distribution	The axial distribution of the power produced in the fuel rods. H(5) Dominant factor in determining peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Power shapes are conservatively set or calculated. PK(0): No votes UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Fuel-clad gap friction coefficient (bonding)	The friction coefficient between the pellet and cladding specified as an initial condition to represent the initial-state of interaction between the two (includes chemical bonding between the fuel and cladding as appropriate. H(0) No votes M(3) Affects heat transfer (beneficial) and could affect the degree of ballooning. L(2) Not a dominant effect during LOCAs. Fuel: N Clad: N Reactor: N Burnup: Y: For higher burnup, more bonding is present. K(0): No votes PK(5): Phenomenon is known but well enough known to be used for a LOCA calculation. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Surface conditions (rewet)	Conditions, e.g., roughness, on the outer surface of the cladding as they affect interaction with the coolant, particularly during rewet. H(1) Affects cladding rewetting and quench location which directly affects peak cladding temperature. M(0) No votes L(5) Does not affect the peak cladding temperature calculation as rewet occurs after the peak cladding temperature is attained. More important for system response and energy release. Fuel: N Clad: N Reactor: N Burnup: N K(5): Surface roughness of cladding in the core at the initiation of the LOCA is well known. PK(1): Large scatter in data. Material dependent and surface condition dependent. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Coolant conditions	Thermal-hydraulic conditions in the coolant channel, including pressure, temperature, quality, void fraction and mass flow rate. H(5) Determines the heat transfer coefficient. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Fluid conditions at the initiation of the LOCA are well known. PK(0): No votes UK(0): No votes
Initial conditions	Rod free volume	The plenum and other free volumes within the fuel rod occupied by the gas. H(5) Can affect the magnitude of burst and blockage as well as timing. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): For a given rod, the free volume can be calculated within 25%. PK(0): No votes UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Gas communication (resistance)	The ability of the gas in the free volume to move axially within the fuel rods, thereby providing uniform gas pressure. H(0) No votes M(0) No votes L(5) Time scale is too long for this to be important. Fuel: N Clad: N Reactor: N Burnup: N K(5): Based on burst data but note that tests were conducted with fresh fuel. PK(1): Uncertainty in the phenomenon. UK(0): No votes
Initial conditions	Pu cluster size (MOX only)	The size and distribution of Plutonium rich agglomerates in MOX fuel. H(0) No votes M(0) No votes L(5) Within expected distribution, the effect is 2nd or 3rd order. Fuel: NA Clad: N Reactor: N Burnup: N K(5): Well characterized. PK(0): No votes UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Pellet cracking representation	Radial and circumferential cracks within the pellet. H(0) No votes M(5) Affects conductivity, stored energy, and gap conductance. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Adequately known. PK(1): Due to uncertainty. UK(0): No votes
Initial conditions	Gadolinium distribution (conductivity effect)	The spatial distributions of gadolinia within the fuel rod that affects the thermal conductivity of the fuel pellets. H(0) No votes M(5) Currently gadolinium rods are not limiting, but they become limiting when the gadolinium burns out in future designs. L(0) No votes Fuel: Y: Gadolinium designed for high burnup could change the ranking to high. Clad: N Reactor: N Burnup: N K(5): Well characterized. PK(0): No votes UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Initial stored energy	The total energy content of the fuel rods initial power conditions before the LOCA. H(5) This phenomenon establishes the starting point. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Known from plant calculations. PK(0): No votes UK(0): No votes
Initial conditions	Initial core pressure drop (grids)	The initial axially-varying pressure within the fuel channel. H(0) No votes M(0) No votes L(5) Does not influence heat transfer coefficients which were previously calculated in system analysis. Fuel: N Clad: N Reactor: N Burnup: N K(5): Well known. PK(0): No votes UK(0): No votes

Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Spallation of oxide layer, cracking	Separation and loss of the cracked oxide layer from the outer surface of the cladding. H(5) Can create weak spots which may result in early ballooning and rupture; creates hydride lens (weak spot). M(1) Rods that are at high burnup usually are not peak cladding temperature limited. L(0) No votes Fuel: N Clad: Y: Could be less important if there is a cladding material that doesn't oxidize as much. Reactor: N Burnup: N K(0): No votes PK(5): Spallation of oxide layer is random and cannot be predicted accurately. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Pellet shape	Changes to the pellet shape from its initial state such as dished or chamfered ends, barrelling or hourglassing as they affect the cladding response. H(0) No votes M(0) No votes L(5) 2nd order effect. Fuel: N Clad: N Reactor: N Burnup: N K(5): Well known. PK(1): Due to pellet cracking. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient boundary conditions	Transient cladding-to-coolant heat transfer (all phases: blowdown refill, reflood and steady state)	Flow-regime-dependent total heat transfer coefficient (including convection and radiation) and fluid temperature for blowdown, refill, and reflood phases. H(5) These are the set of controlling phenomena that determine how the cladding will respond. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): There are uncertainties associated with the input to the two-phase heat transfer coefficients and the heat transfer coefficients themselves. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient boundary conditions	Transient and steady state power distributions	Provides the spatial and temporal power and stored energy distributions in the fuel rod. H(5) Major source of energy that drives the peak cladding calculation. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Decay heat is well known. PK(0): No votes UK(0): No votes
Transient boundary conditions	Transient coolant conditions	Spatial and temporal variation of the coolant conditions within the fuel channel. H(5) Establishes the heat sink. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): There are uncertainties associated with the input to the two-phase heat transfer coefficients and the heat transfer coefficients themselves. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Plastic deformation of cladding (thinning, ballooning and burst)	Irreversible changes in cladding dimensions caused by pressure differentials or mechanical loadings at high temperatures. If cladding burst occurs, the final plastic deformation at the burst location is characterized by the burst strain. H(5) Affects gap heat transfer, inside and outside oxidation, and location of the peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Given temperatures and pressures, cladding plastic deformation can be calculated with adequate accuracy. PK(1): Same as K but uncertainty is larger. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Direct gas pressure loading	The combination of available fission gas combined with the fill gas in determining an internal pressurization. H(5) A driver in determining clad strain and burst. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Universal gas law is adequate. PK(0): No votes UK(0): No votes
Fuel rod response	Quench loading of clad	Thermal loading due to quenching of the fuel rod by the coolant. H(0) No votes M(3) Could determine long-term coolability. L(2) Assumes we stay below 17% criterion. Fuel: N Clad: N Reactor: N Burnup: N K(5): Temperature distribution in the cladding can be calculated. PK(1): Gap conductance is variable during the process. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Thermal deformation of pellet and cladding	Reversible changes in pellet and cladding dimensions caused by thermal expansion. H(0) No votes M(0) No votes L(5) Not significant compared to plastic deformation. Fuel: N Clad: N Reactor: N Burnup: N K(5): Temperature distribution can be accurately calculated. PK(0): No votes UK(0): No votes
Fuel rod response	Elastic deformation of cladding	Reversible changes in cladding dimensions caused by pressure differentials or mechanical loadings. H(0) No votes M(4) Not the dominant effect. L(0) Not the dominant effect but even lower influence. Fuel: N Clad: N Reactor: N Burnup: N K(5): Well known. PK(0): No votes UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Fission gas release	The release of fission gas during a transient through the pellet into the free volume. H(0) No votes M(0) No votes L(5) Temperature below threshold for fission gas release. Fuel: N Clad: N Reactor: N Burnup: N K(5): Fuel temperature below the threshold. PK(0): No votes UK(0): No votes
Fuel rod response	Pellet swelling	Fission gas contribution to the swelling of the pellet. H(0) No votes M(0) No votes L(5) Temperature below threshold for fission gas release. Fuel: N Clad: N Reactor: N Burnup: N K(5): Well known. PK(0): No votes UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Axial and radial temperature distributions	Radial and axial variation in temperature. H(5) Determines the heat transfer rate to the cladding and coolant and the peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Given the boundary conditions, heat conduction analysis method is well established and accurate. PK(0): No votes UK(0): No votes

Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Heat resistances in fuel	The resistances offered by the fuel to the flow of thermal energy from regions of high temperature to regions of lower temperature. The resistance is dependent upon path length and thermal conductivity, which change with burnup and other processes, e.g., the buildup of oxide on the cladding surfaces. H(5) Used in determining the temperature response. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Known well at locations other than the burst location, even at the burst location the fuel resistance is well known prior to the burst. PK(2): During ballooning, the possibility of fuel relocation increases the uncertainty. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Heat resistances in gap	The resistances offered by the gap to the flow of thermal energy from regions of high temperature to regions of lower temperature. The resistance is dependent upon path length and thermal conductivity, which change with burnup and other processes, e.g., the buildup of oxide on the cladding surfaces. H(5) Used in determining the temperature response. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(6): During ballooning, the possibility of fuel relocation increases the uncertainty. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Heat resistances in clad	The resistances offered by the clad to the flow of thermal energy from regions of high temperature to regions of lower temperature. The resistance is dependent upon path length and thermal conductivity, which change with burnup and other processes, e.g., the buildup of oxide on the cladding surfaces. H(1) A key part of the calculation of heat flux. M(5) A small contribution to heat reistance. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Heat resistance of cladding is well known at possible temperatures. PK(0): No votes UK(0): No votes

DRAFT

Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Heat resistances in oxide	The resistances offered by the oxide to the flow of thermal energy from regions of high temperature to regions of lower temperature. The resistance is dependent upon path length and thermal conductivity, which change with burnup and other processes, e.g., the buildup of oxide on the cladding surfaces. H(5) Can be a large contribution considering effects of oxide delamination. M(1) High burnup rods not peak cladding temperature limiting. L(0) No votes Fuel: N Clad: Y: Effect can be smaller if new cladding does not oxidize as readily. Reactor: N Burnup: N K(0): No votes PK(6): Relatively high uncertainty due to delamination. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Cladding azimuthal temperature distributions	Circumferential variation in temperature. H(1) Determines when burst occurs and the degree of blockage. M(5) Can affect timing and degree of strain at burst. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(6): High uncertainty in predicting fragmentation. High uncertainty in predicting azimuthal temperature distributions. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Cladding oxidation magnitude (ID/OD)	Change in cladding oxidation during the transient. H(5) Can be limiting for those cases that are ruptured node limited – also affects meeting the local oxidation limit. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(2): For a given set of conditions, oxidation can be calculated with adequate accuracy. PK(4): Uncertainty in initial oxidation and uncertainty in application to complex situations. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Metal-water reaction heat addition	The additional heat generated in the cladding due to metal-water reactions. H(5) Can be important above certain temperature for inside and outside oxidation. M(1) Effect is small unless cladding temperatures exceed 2200 °F. Phenomenon is exponential with temperature. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: Y: Less important for high burnup. K(6): Mechanism is well known. PK(0): No votes UK(0): No votes
Fuel rod response	Size of burst opening	Geometry of the burst region. H(6) An important phenomenon as it affects the degree of blockage and fuel dispersal and relocation. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Evidence to indicate that the burst opening is smaller for high burnup. UK(1): Not known sufficiently well to calculate.

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Burst criteria	Combinations of physical parameters which are expected to cause cladding burst. For example, NUREG-0630 correlates burst temperature as a function of engineering hoop stress and heatup rate. H(6) Determines the timing and location of cladding burst – effects the calculation of peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(1): The state of the art is such that the burst criteria can be accurately calculated. PK(5): The current criteria do not include the important time effect. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Cladding phase changes	Change in the cladding microstructure from alpha phase (low temperature) to the alpha + beta phase, to beta phase (high temperature). The phase change energy of transformation can effectively increase the cladding specific heat over the transition temperature range. The phase change affects ductility resulting in significant effects of plastic deformation (creep rate and burst). Changes in cladding alloy or hydrogen content affect the transition temperature changes. H(6) All these effects determine cladding material properties that determine the degree of strain and the timing of the burst. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(6): Given the temperature, the phase transition is well known. PK(0): No votes UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Time of burst	The amount of time elapsed between initiation of the LOCA and the predicted cladding burst. H(6) Has a significant impact on peak cladding temperature calculation. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(6): Temperature range in which burst occurs takes place during a limited period of the LOCA transient (quickly). UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Location of burst	The axial position at which cladding burst and flow blockage occur. H(6) Has a significant impact on peak cladding temperature calculation. Has a significant impact on peak cladding temperature calculation and depends on grid location. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Burst location is dominated by power shape. PK(2): There are other factors that enter into the determination of the burst location. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Spacer grid constraint	Constraints imposed by the grids on cladding deformations. H(1) Spacer grids determine the amount of cooling which in turn determines where the blockage occurs and the degree of co-planar blockage. M(3) Might calculate the wrong burst location if ignore grid. L(2) The limiting location is usually not a grid location – a 2nd order effect. Fuel: N Clad: N Reactor: N Burnup: Y: Less important for higher burnup. K(0): No votes PK(6): Analytical capability exists to be able to calculate with adequate accuracy. No code can calculate this. UK(0): No votes
Fuel rod response	Pellet to cladding bonding	Absence of a gap between the fuel and the cladding due to the bonding of the pellets to the cladding. H(2) May reduce the effect of inside oxidation. M(4) Not believed to be a dominant effect. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(6): Insufficient data. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Localized effects	Stress risers within the cladding at discrete locations, arising from various sources, including the pellet shape as well as undetected defects in the cladding. H(0) No votes M(0) No votes L(5) Data used to judge effects of rod failure already includes this effect. Fuel: N Clad: N Reactor: N Burnup: Y: Localized effect increases with burnup. K(0): No votes PK(0): No votes UK(5): Defects occur at random.
Fuel rod response	Biaxiality	The dependence of cladding deformation and burst on the multi-dimensional stress state. H(0) No votes M(2) Affects deformation during ballooning phase. L(3) a small effect on ballooning per existing analyses. Fuel: N Clad: N Reactor: N Burnup: N K(5): Given the temperature of the cladding, this behavior can be calculated with accuracy. PK(0): No votes UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Fuel relocation	Movement of pellet fragments into a region where cladding plastic deformation (ballooning or burst) has occurred. Fuel relocation changes the local linear heat rate and affects gap conductance and fuel thermal resistance. H(1) It is plant dependent. If the plant is burst node limited, this can make the event worse. M(5) Has a modest impact on the local linear heat rate. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(6): A limited amount of data available. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Grain boundary decohesion	Separation of grains under the effect of gas bubble pressure when cladding confinement is lost. H(0) No votes M(0) No votes L(5) Not important for a LOCA. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Insufficient data exists to apply to situations other than those that have been directly observed. UK(0): No votes
Fuel rod response	Evolution of pellet stress state	Changes in pellet stresses due to the time-dependent temperature, pellet cladding interactions, internal gas bubble pressure, etc. H(0) No votes M(0) No votes L(5) Not important for LOCA event. Fuel: N Clad: N Reactor: N Burnup: N K(5): Given the conditions, this phenomenon can be accurately calculated. PK(0): No votes UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Multiple rod mechanical effects	Rod-to-rod and rod-to-channel thermal and mechanical interactions	The thermal and mechanical effects of adjacent rods and/or channel box on the fuel rod being modeled in the code. H(1) More important in CE designs due to large guide thimbles. M(5) Medium importance for BWRs (radiation). L(0) No votes Fuel: N Clad: N Reactor: Y: More important for BWRs. Burnup: N K(5): Mechanical interaction is ranked low and is less known. Heat transfer is well known. PK(0): No votes UK(0): No votes
Properties	Fracture stress of oxide	The tensile strength of the zirconium oxide. H(0) No votes M(0) No votes L(5) Offers no additional strength to cladding. Fuel: N Clad: N Reactor: N Burnup: N K(5): Given conditions, this phenomenon can be accurately calculated. PK(0): No votes UK(0): No votes

DRAFT

Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Properties	Yield stress in compression	Yield strength of the cladding as it affects rod deformations due to axial constraints. H(0) No votes M(0) No votes L(5) Rods don't go into compression mode. Fuel: N Clad: N Reactor: N Burnup: N K(5): Given conditions, this phenomenon can be accurately calculated. PK(0): No votes UK(0): No votes
Properties	Heat capacities of fuel and cladding	Self explanatory. H(5) Used to determine fuel and cladding thermal response. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): The properties are well known. PK(0): No votes UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Properties	Thermal conductivities of fuel and cladding	Self explanatory. H(5) Used to determine fuel and cladding thermal response. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): The properties are well known. PK(0): No votes UK(0): No votes
Properties	Strain rate effects	Strain rate effects as they change the stress strain curve in terms of affecting the yield stress and the deformation behavior in the plastic regime. H(0) No votes M(0) No votes L(5) Strain rate is low during LOCA. Fuel: N Clad: N Reactor: N Burnup: N K(5): The material response is adequately known. PK(0): No votes UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Properties	Anisotropy	The variation of cladding properties along the different coordinate directions. H(0) No votes M(0) No votes L(5) Anisotropy disappears with fluence. Fuel: N Clad: N Reactor: N Burnup: N K(5): This effect is well known. PK(0): No votes UK(0): No votes
Transient cladding-to-coolant heat transfer	Rod-to-spacer grid thermal hydraulic interaction	The enhanced convective heat transfer effects downstream of the spacer grids due to mixing and flow redistribution for single or two-phase flows. H(5) Has significant impact on axial variation of heat transfer coefficient and calculation of cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Data are available but more data are needed. UK(0): No votes

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Table C-1
PWR and BWR LOCA Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient cladding-to-coolant heat transfer	Spacer grid rewetting and droplet breakup	The wetting of spacer grids, which enhances the interfacial heat transfer at and downstream of the spacer grids. H(5) Has significant impact on axial variation of heat transfer coefficient and calculation of cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Incomplete droplet breakup data. UK(0): No votes

APPENDIX D

CATEGORY D
SEPARATE EFFECT TESTING

PHENOMENA DESCRIPTIONS AND RATIONALES FOR IMPORTANCE RANKING, APPLICABILITY, AND UNCERTAINTY

This appendix provides a description for each phenomenon appearing in Table 3-4, Separate Effect Testing PIRT. Entries in the Table D-1, columns 1 and 2, follow the same order as in Table 3-5. Table D-1, column 3, also documents the PIRT-panel developed rationales for three types of Panel findings.

First, rationales are provided for the importance (High, Medium, or Low) assigned by the panel to each phenomenon. Because importance ranking was established by a vote of the panel members, a rationale is provided whenever one or more panel members voted a particular rank, i.e., High, Medium or Low. If there were no votes for a given importance rank, "No votes" is entered.

Second, the PIRT panel considered the applicability of the baseline PIRT to a broader set of circumstances, e.g., different fuel arrays, cladding types, reactor types, and burnups to 75 GWd/t. The specific question addressed by the PIRT panel was as follows: "Could the importance ranking assigned for the given phenomenon in the baseline PIRT be for different for other fuel arrays, cladding types, reactor types, or burnups?" If this question is answered with a "no", the following entry appears in Table C-1: "Baseline PIRT importance rank is applicable." If this question is answered with a "yes", the rationale is entered. Additional details are presented in the footnotes to Table 3-5.

Third, the PIRT panel considered the current state of knowledge or uncertainty regarding each phenomenon. The phenomenon is characterized as "known (K)" if approximately 75-100% of full knowledge and understanding of the phenomenon exists. The phenomenon is characterized as "partially known (PK)" if between 25-75% of full knowledge and understanding of the phenomenon exists. The phenomenon is characterized as "unknown (UK)"if less than 25% of full knowledge and understanding of the phenomenon exists. Because the uncertainty ranking was established by a vote of the panel members, a rationale is provided whenever one or more panel members voted a particular uncertainty, i.e., known, partially known, or unknown. If there were no votes for a given uncertainty level, "No votes" is entered

There were several phenomena for which no importance rank was recorded. In such cases "No rationale recorded" is entered.

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PWR and BWR LOCA
Category D– Separate Effect Testing

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Oxidation rate, oxygen distribution, effect of chemistry on solubility (vote=15) Separate effect test to measure the steam oxidation kinetics at high temperature in Zirconium alloys used for cladding.	Specimen selection: Alloy type	Composition or designation of the metal utilized in fuel-rod fabrication **Definitions notes:** **Definitions provided by member during ballot are indicated by ****** **If vote made with no definition, "Need definition" entered** **Otherwise, definition entered available at time of ballot.** H(3) Data (B&W-10227) or Toronto show that the 2nd layer develops differently on different alloys. Initial oxide layer may be different between alloys and thus behave differently. M(2) Similar to rationale for high but the oxide kinetics do not change and the other differences may not affect brittleness. L(0) No votes. Fuel: N Clad: NA Reactor: N Burnup: N K(3): ???? PK(2): ???? UK(0): ????

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Thickness and morphology of pre-existing oxide	****The total amount of oxide formed on the cladding and whether the oxidation is uniform or nodular, and whether there is extensive cracking and spalling. H(1) Thickness and morphology controls passage to the metal, even though the oxidation rates are the same. M(2) Hydrogen pickup during corrosion may affect oxide rates. Some early irregularities in oxide rate data exist and may be due to corrosion layer. L(2) Data (French and Japan) show that only the thin dense oxide layer controls the oxidation rate at high temperature and this layer is independent of the initial oxide. Fuel: N Clad: NA Reactor: N Burnup: N K(2): Data PK(3): Data (incomplete) UK(0): No votes

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Burnup, including fluence	The amount of burnup to which the fuel rod used for the specimen was exposed. H(3) Burnup per se may not be so important but there could be effects such as precipitate dissolution for which testing is needed. M(1) Burnup per se may not be so important but there could be effects such as precipitate dissolution for which testing is needed, but the effect is not expected to be so pronounced. Discovery of unknown effects may occur if testing takes place, e.g., conformation or annealing effects. L(1) Irradiation damage is expected to be annealed out. Fuel: N Clad: N Reactor: N Burnup: NA K(1): Data PK(4): Data, judgement UK(0): No votes

DRAFT

PWR and BWR LOCA
Category D– Separate Effect Testing

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Pre-existing hydrogen content and distribution	Amount and distribution of hydrogen associated with fuel rod clad segment. This hydrogen may be in solution in the metal or may exist combined with the metal as a discrete hydride phase. H(1) Affects oxygen repartition during oxidation and oxygen solubility in the beta phase. M(3) Initial amount of hydrogen has a slight impact on the cladding strain during the ballooning phase and a very low impact on oxidation at high temperature and behavior upon quench.. Potential impact on post-quench mechanical tests. The initial H distribution has no impact. High concentration of hydrogen stabilizes beta phase and is conducive to thicker layer of load-bearing prior beta phase. The initial H distribution is erased by the high temperature excursion. The total amount of H may have a moderate impact on kinetics. L(1) The available testing by the Japanese and French indicate a relatively minor effect of hydrogen content on unirradiated or irradiated cladding high temperature oxidation Fuel: N Clad: NA Reactor: N Burnup: NA K(2): Data PK(2): Data, judgement UK(): No votes

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Oxygen potential	Need definition H(3) The oxygen availability directly controls the alpha and oxide layer developments and the hydrogen pickup. Condition of steam starvation must be avoided to have a valid test.. The oxygen potential is the boundary condition that determines oxidation rate. M(1) The development of an appropriate environment is essential to obtaining meaningful results. However, the measurement of oxygen potential may not be necessary to ensure a prototypical environment L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(1): Data. Judgement PK(2): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Temperature and time	Measurement of the time-varying temperature. H(5) May affect oxygen distribution and hydrogen pickup. key parameters needed to analyze the tests. Since the corrosion process is such a strong function of temperature, accurate measurement of the temperature during the test is essential to providing meaningful results. Test results are very sensitive to accuracy of temperature and time measured. Temperature history is obviously crucial. M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data, Judgement PK(2): Data, Judgement UK():

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PWR and BWR LOCA
Category D– Separate Effect Testing

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Motta comment: It was not clear to me whether this was an independent parameter or an ersatz for something else. This is another "insight" into the process. It's better to put things explicitly even if long winded (or at least have VERY explicit definitions) as the memory evanesces quickly	Conduct of Test-During Total steam pressure	Need definition H() No votes. M(3) Available experimental results do not show large effects for low burnup Zircaloy; to be confirmed at high burnup and for alternative cladding alloys. Not a key parameter but should be measured to check the experimental conditions are the same. Available testing information indicates measureable differences in high temperature cladding corrosion rate for different steam pressures. L(1) As long as steam starvation is prevented, total steam pressure is less important. Fuel: N Clad: N Reactor: N Burnup: N K(3): Data, Judgement PK(1): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Weight gain	****On-line measurement of the total amount of oxygen absorbed during the high temperature oxidation phase. H(4) Very important parameter to measure because it is directly linked with the equivalent cladding reacted (ECR) used for a LOCA criterion. Key parameter used to interpretate the tests. Less acurate than direct O measurement (integrate Temperature distribution effects and end effects) but very useful in relative. Weight gain is the most common and convenient parameter that is used to determine exothermic oxidation heat and the degree of oxidation. This is one of the main indicators of the primary effect we want to measure. M(1) Weight gain is a primary measure of corrosion, however, the more important measure in this case would be performed by metallography (differentiation between oxide, oxygen-stabilized alpha-phase, and remaining beta phase). L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(5): Data, Experience, Judgement PK(): No votes. UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Steam consumption	**** On-line measurement of the level of oxidation during the LOCA transient H(1) This is a primary indicator of oxidation. M(2) Cross-check measurement for the weight gain. Useful data but less precise than the post test measurement when the high temperature oxidation is non-uniform along the rod L(2) The use of steam consumption was suggested as an alternate, independent assessment of oxygen absorbed, however, the more direct measurement is performed with metallography and weight gain. Steam consumption is not easily measured and is not necessarily an accurate indication of the degree of total oxidation (because of steam condensation). Fuel: N Clad: N Reactor: N Burnup: N K(3): Data, Experience, Judgement PK(2): Judgement UK(): No votes.

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PWR and BWR LOCA
Category D– Separate Effect Testing

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During One-sided vs. two-sided	**** When the cladding bursts during the blow down phase of the LOCA transient, the high temperature oxidation occurs on both sides of the clad. If the cladding doesn't burst, the oxidation is one sided. H(2) Two-sided oxidation is important in order to reproduce the specific oxidation conditions inside the balloon (stagnant steam conditions inducing a higher hydrogen pickup). A true simulation of the actual condition is essential to avoid overlooking unanticipated effect; such as the role of inner surface fission products, presence of a zirconium liner, or other possible differences M(2) Both kind of tests are doable. The analysis should take into account the test conditions. Two-sided oxidation may have slightly different kinetics; at least it is worth investigating. L(1) High-temperature oxidation is controlled primarily by the process of oxygen transport across the oxide layer. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data PK(3): Data, Judgement: Prior work has shown, for example, that the presence of a zirconium liner does not significantly affect the cladding high temperature corrosion behavior. However, all possible effects have not necessarily been quantified. UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-PTE Oxide thickness	**** Post test measurement of the oxide thickness that developed during the high temperature phase of the LOCA transient. H(5) One of the most pertinent measurements. Oxide thickness is the most important parameter of oxidation. Key parameter for the interpretation and analysis of the test. Post test metallography is the primary and most reliable quantification, however the measurement is not necessarily just oxide thickness, also region of oxygen-stabilized alpha layer and remaining beta layer. Useful parameter to measure primary item studied. M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(3): Data, Experience PK(1): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-PTE Chacteristic α–β morphology	**** Measurement of the thicknesses of the different metallurgical layers that formed during the LOCA transient. H(5) Key parameter to analyze the test. Post test metallography is the primary and most reliable quantification, however the measurement is not necessarily just oxide thickness, also region of oxygen-stabilized alpha layer and remaining beta layer. Alpha and beta layer thicknesses and the degree of alpha "incursion" are important oxidation parameters that influence the mechanical properties of the cladding. Relative amounts of alpha and beta determine the behavior of oxidized clad. M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(3): Data, Experience, Judgement PK(2): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-PTE Oxygen distribution	Distribution of oxide either dissolved or existing as an oxide phase in the cladding. H(5) Oxygen content in the beta phase is important for embrittlement. Key parameter that governs the behavior upon quench of the cladding. Post test metallography is the primary and most reliable quantification, however the measurement is not necessarily just oxide thickness, also region of oxygen-stabilized alpha layer and remaining beta layer. Distribution of oxygen in prior beta layers is an important oxidation parameter that strongly influences the mechanical properties. M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data, Experience, Judgement PK(2): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-PTE Hydrogen pickup and distribution	**** Amount and distribution of H absorbed by the cladding during the LOCA transient. H(3) Hydrogen pickup in the beta phase is important for brittleness. The amount of H usually picked-up is small. It can be locally very high in case of early failure of the cladding during the ballooning phase followed with steam ingress. Hydrogen content and distribution in the prior beta layer are important parameters that influence the mechanical properties of the cladding. M(2) Prior work by the Japanese and French have shown the pre- and post-test hydrogen content and distribution to be not so influential for practically achieveable hydrogen levels, however, this is an item of active interest and deserves characterization. L() No votes. Fuel: N Clad: N Reactor: N Burnup: Y(1): More important for high-burnup fuel K(3): Data, Judgement PK(2): Data, Judgement UK(): No votes.

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PWR and BWR LOCA
Category D– Separate Effect Testing

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Quench tests, quench rate, Tquench, etc. (vote=14) Separate effect test to determine the thermal shock resistance of cladding when quenched after high temperature oxidation.	Specimen selection: Hydrogen content and distribution	Amount and distribution of hydrogen associated with fuel rod clad segment. This hydrogen may be in solution in the metal or may exist combined with the metal as a discrete hydride phase. H(2) Affects oxygen solubility in the beta phase and post-quench ductility. Hydride dissolves during oxidation at high temperatures and most hydrogen atoms are concentrated in the beta phase. Hydrogen content and distribution in the transformed beta phase are important parameters that influence clad resistance to thermal-shock failure. M(2) Data show low impact of H on clad behavior upon quench. Prior testing has demonstrated that quench behavior is not significantly affected by the amount of prior hydrogen (oxygen embrittlement is more important), distribution of prior hydrogen (homogenization occurs during the high temperature period), or hydrogen absorbed during the high temperature oxidation reaction (hydrogen absorption is minimal). However, this is an item of active interest and deserves a characterization. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data PK(2): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Alloy type	Composition or designation of the metal utilized in fuel-rod fabrication H(2) May affect oxygen distribution and hydrogen pickup. Stability of beta phase and mechanical properties of the load-bearing prior beta layer are significantly influenced by the addition of Nb, therefore, thermal-shock resistance of M5 and Zirlo is expected to differ from that of Zircaloy. M(1) In general, differences among the characterized zirconium based materials have shown differences in high-temperature oxidation and quench behavior to be relatively minor. However, specific details on the newer materials are not available to the reviewer and so bets are hedged. L(1) Data show no significant impact of the Alloy type on the behavior upon quench Fuel: Y(1): M5- or Zirlo-clad fuels Clad: N Reactor: Y(1): PWR Burnup: N K(1): Data PK(2): Data UK(1): Judgement

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Thickness and morphology of pre-existing oxide	****The total amount of oxide formed on the cladding and whether the oxidation is uniform or nodular, and whether there is extensive cracking and spalling. H(2) These parameters influence the degree of transient oxidation and hydrogen uptake, the two properties that strongly influence clad resistance to thermal shock. It is important to use representative cladding even though data shows little effect. M(2) Oxidation characteristics are less important than associated hydrogen pickup. However, non-prototypical fabrication conditions may artificially enhance its impact. For example, oxide layers produced under a gaseous mixture of noble gas and steam is dense and protective while oxide layer produced under irradiation is defective and non-protective. Data show that pre-existing oxide has no significant impact on the clad resistance upon quench.. Nevertheless the clad thinning associated to a thick pre-existing oxide layer affects slightly the stress field in the cladding and the overall clad behavior during the LOCA transient. In general, differences among the characterized zirconium based materials have shown differences in high-temperature oxidation and quench behavior to be relatively minor. However, specific details on the newer materials are not available to the reviewer and so bets are hedged. L(1) No rationale given. Fuel: N Clad: N Reactor: N Burnup: N K(3): Data PK(1): Data UK(1): No rationale provided

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Burnup	The amount of burnup to which the fuel rod used for the specimen was exposed. H(2) High burnup alters several important properties of cladding and the nature of pellet-cladding interface which influence the resistance to thermal-shock failure. Full rod (French): fuel morphology (fragmentation, rim characteristics, bonding, etc. are important). M(3) The available testing information suggests that the effects of irradiation hardening, prior oxide thickness, and prior hydrogen content do not significantly affect quench behavior for practically achievable levels of these parameters. However, high burnup specimens should be selected to address the question of unknown or previously otherwise uncharacterized effects. Empty rod (French): fuel morphology (fragmentation, rim characteristics, bonding, etc. is of moderate importance).. Independently of the other degradation variables (O, H, etc) burnup may not be important but it's good to preserve protypicality. L(0) The clad temperature during a LOCA transient is large enough to anneal all irradiation defects. At the time of quench there is no irradiation damages left in the cladding. Prior testing by the French and Japanese have shown a relatively minor if any effect of pre-existing oxide thickness. The greater consideration would be the effect of pre-existing hydrogen content and even that has been demonstrated to result in a minor, if any effect on quench behavior. Fuel: Y(1): MOX (agglomerates) in case of full rod Clad: N Reactor: N Burnup: N K(2): Data PK(2): Data, Judgement: Much is known (Data), but this testing is intended to also address the unknown. UK(1): No votes.

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PWR and BWR LOCA
Category D– Separate Effect Testing

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Axial constraints	Manner in which test specimen is constrained by fittings. H(5) Phebus 219 rod 18 shows that constraints can affect test outcome. Japanese test shows the restraint can affect brittleness results. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(4): Data UK(1): Data (incomplete), judgement

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Azimuthal quenching	**** The rod environment (guide tubes, grids, etc.) affects the local coolant flow and temperature. As a consequence the quench of the cladding may not be azimuthally uniform. H(1) This is the type of effect that should be tested using a limiting case so that it can be disposed of as a problem or investigated further. M(3) In rupture processes, any asymmetry in stress field enhances the rupture. Impact is expected to be of the second order. It will be very difficult to simulate a prototypical azimuthal quenching. Effects can be hypothesized that might affect quench behavior, however quantification does not exist. It is noted that some variations are likely implicitly included (although unquantified) in the existing data base. L(1) Azimuthally localized nonuniform partial quenching is less prototypic and should be avoided in the test. Fuel: N Clad: N Reactor: N Burnup: N K(): No votes. PK(4): Data, Judgement UK(1): No rationale provided

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Empty/full	Conduct of test using specimens that have either had the fuel removed (empty) or the fuel remains (full). H(3) In the case of fuel relocated into the ballooning, the clad is less susceptible to rewetting due to enhanced heat transfer to the cladding associated with the stored energy and the residual power of the fuel. The desire is to perform a separate effects test to understand the behavior of the cladding, as opposed to confusing interactions introduced by the presence of fuel pellets. The effect of the fuel pellets will be assessed during the intergral testing. Intact fuel and the state of fuel-cladding gap or bonding influence important parameters such as clad ID oxidation, hydrogen uptake, and clad mechanical constraints. M(2) Data showing the importance of the presence of the fuel within the rod during the quenching are not available. Needs testing. L() No votes. Fuel: N Clad: N Reactor: N Burnup: Y(1): More important at high burnup. K(1): ANL and JAERI data, judgment PK(4): Data, Judgement: Some pellet effects have been hypothesized, but the point here is that this is to be a separate effects test – and so it should be a separate effects test (no pellets). UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During One-sided vs two-sided	****The quench is applied either on the external side of the cladding or on both sides. The latter simulates the case of a rod that burst during the blow down phase. H(1) The magnitudes of total oxidation, hydrogen pickup, temperature gradient during quench, and thermal stress are influenced significantly by this choice. M(4) In a real quench process, at the balloon height, the cladding suffers both mechanisms, i.e., two-sided near the burst opening and one-sided at the opposite azimuth. Data show low impact on the result. The thought is that the primary parameter affecting quench behavior is the remaining beta phase, and not so much where that is (ID in one-sided test or mid-thickness on two-sided tests). However, there should be at least a few tests of the actual condition (two-sided) to confirm that a significant difference in performance does not occur. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(1): Data PK(4): Data, Judgment UK(): No votes.

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PWR and BWR LOCA
Category D– Separate Effect Testing

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Cooldown before quench	****To be more prototypical the cladding needs to cool down naturally from the oxidation temperature to the quenching temperature (around 700-800 °C) H(5) The important parameter is the relative values of the beta and alpha transition temperatures, which controls some mechanical properties. The test should be as prototypical as possible to avoid undesirable artifacts. French testing has demonstrated a significant difference between a fast quench and a fast quench preceded by a slow cooldown phase that is more prototypical of the actual condition. Cooldown rate strongly influences O and H distributions and the microstructure and the mechanical properties of the prior beta layer. M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(3): Data PK(2): Data, Judgement UK(): No votes.

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PWR and BWR LOCA
Category D– Separate Effect Testing

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Clad temperature before quench	**** Clad temperature at the time the quench occurs. It depends on the rod environnment. It has an impact on the metallurgical morphology of the clad. H(4) The important parameter is the relative values of the beta and alpha transition temperatures, which controls some mechanical properties. It has an impact on the alpha-beta phase distribution. Should be as prototypical as possible. Whether quench occurs before or after the completion of beta-to-alpha phase transformation is a major parameter that influences the magnitude of thermal stress and the properties of the prior-beta phase. M(1) Hobson's ring tests showed that even for the same level of oxidation, the mechanical properties were different for different high temperature levels. This difference may or may not affect the quench behavior, and may or may not be significant when all temperatures are below 2200 F, however, it suggests that a range of pre-quench temperatures be explored to confirm no unexpected differences in behavior exist. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data, Judgement PK(3): Data, Judgement UK(): No votes.

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Category D– Separate Effect Testing

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Cycling of quenching	Repeated loading of the test segment via dryout followed by quenching. H(1) No rationale given. M(2) Before permanent reflood, a cladding may encounter several partial and temporary rewetting and dryout periods. This phenomenon may enhance the clad rim. low impact of the cycles are expected on the overall behavior of the cladding. Should be checked through a separate effect tests series (phase equilibria and transformation kinetics tests). L(2) The most severe thermal shock is produced at the first quenching. Not sure why this is being considered. It's not the expected case. Fuel: N Clad: N Reactor: N Burnup: N K(): No votes. PK(2): Data, Judgement UK(3): No information on cyclic quenching, but also not convinced it will happen.

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Temperature history	Measurement of the time-varying temperature. H(3) May affect oxygen distribution and hydrogen pickup. This is the primary factor that determines oxidation, hydrogen uptake, and the mechanical properties of the load-bearing prior beta layer. Temperature history determines everything. M(2) The key parameter is the clad temperature before quench. To measure the local clad temperature during the quench might be useful for the analysis but the measurement has not to be intrusive (risk of experimental artifacts). Knowledge of the actual temperature prior to the slow cool down phase, and during the slow cool down phase are important to know that we attained the desired pre-quench conditions. However, measurement during the quench is less critical (you get what you get and will likely not be able to measure it precisely). L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data, judgement PK(3): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Pre-thinning of cladding/pre-burst	****The specimen has experienced the ballooning phase of the LOCA transient before being quenche. H(3) The pre-heat state promotes external hydriding by stagnant steam near the ballooned area. The idea here was that the cladding tested should represent the as-thinned condition resulting from pre-transient oxidation, since the remaining metal thickness pre-test determines the remaining ductile ligament after high temperature oxidation (as opposed to using the a section of the fuel rod for the test that exhibits unusually low corrosion (like the bottom of the rod for PWRs)..Since this pre-transient metal loss can be significant (perhaps 10%), this effect can significantly influence the quench test results by correspondingly reducing the remaining ductile region. Pre-thinning influences directly the thickness of the load-bearing prior-beat layer available for a given transient as well as the magnitude of thermal stress. Pre-burst geometry strongly influences the clad ID-side oxidation and hydrogen uptake. M(2) The clad thinning of the ballooned area of the cladding can be taken into account through calculation (geometrical effect only).. The residual stresses related to the clad straining are annealed during the high temperature oxidation phase. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data PK(2): Data, Judgement UK(): No votes.

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Quench mass flow rate	****Amount of water used to quench the rod. H() M(1) Important for the thermal-hydraulic conditions. L(3) low impact is expected. The quench mass flow rate can affect the effectiveness of the quench. However, it is expected that a significant variation in mass flow rate can be permitted and will result in effectively equivalent quench characteristics. Enough water flow should be allowed to ensure wetting in full extent. Fuel: N Clad: N Reactor: N Burnup: N K(): PK(4): Data, Calculation, Judgement UK():

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-PTE Equivalent cladding reacted (ECR) at location of failure	****The percentage of Zr atoms that would have reacted with oxygen to form Zr02 if all oxygen absorbed into the cladding were used to form ZrO2. H(6) Primary parameter used to understand, extend and evaluate results. M(0) L(0) Fuel: N Clad: N Reactor: N Burnup: N K(4): Data PK(2): Judgement based on data and calculations UK(0):

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-PTE Metallography	**** Measurement of the phases distribution in the cladding. Motta alternative definition: Metallographic examination to determine the morphology of the material, and which can be related to phase formation during quench. H(5) One of the most pertinent measurements. Confirms the temperature history of the cladding and the assessment of ECR. Metallography is the primary means to determine the degree of oxidation, phase structure, and the microstructure of the prior beta layer. One of the main reasons to perform the test M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(3): Data, Judgement PK(2): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-PTE Fragment/non-fragment	**** Deterrnine if the cladding embrittlement has led to cladding fragmentation H(5) Important information. Fragmentation of the cladding means risk of fuel dispersal and subsequent coolability concern. This item represents a characterization of the post-quench condition relative to the extent of damage. Since the primary issue is one of maintenance of coolable geometry, this characterization could be very useful in assessing the true challenge to the coolable geometry condition. Determines cladding integrity and susceptibility to potential fuel release and washout; primary objective of test. Easy to do and important. M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data, judgement PK(3): Data, Judgement UK(): No votes.

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-PTE Charactgerization of tubing integrity	**** Perform leak test on the cladding to detect a potential crack. H(4) Primary objective of test. Agree with the medium definition but give it more weight. M(1) To establish the limit of failure upon quench the cladding integrity has to be defined and checked. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data, Judgement PK3): Data, Judgement UK(): No votes.

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Phase equilibria and transformation kinetics-chemistry effects (vote=11) Measurement of phase equilibria and phase transformation kinetics that can provide fundamental data relevant to the cladding behavior during LOCA events.	Specimen selection: Hydrogen content and distribution	****Amount of hydrogen in the sample and where it is located. H(4) Hydrogen affects the alpha, alpha plus beta, and beta boundaries. Data show that hydrogen content has an impact on phase transformation temperature and kinetics. Hydrogen is a strong beta stabilizer which influences phase equilibria, transformation kinetics, and the structure of prior beta layer. M(1) This type of information is useful in explaining, and possibly extrapolating the observations, but does not represent direct confirmation that criteria are met or not met.. As such this whole category is rated at a lower level than some of the other more performance related characterizations. L() No votes. Fuel: N Clad: Y(1): More important for M5 and Zirlo. Reactor: N Burnup: Y(1): More important for high-burnup fuel. K(3): Data PK(2): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Alloy type	Composition or designation of the metal utilized in fuel-rod fabrication H(4) Alloying elements such as Sn and Nb affect the alpha, alpha plus beta, and beta boundaries. Nb-bearing M5 and Zirlo behave significantly different from Zircaloys. Affects the phase equilibria and the transformation kinetics. M(1) This type of information is useful in explaining, and possibly extrapolating the observations, but does not represent direct confirmation that criteria are met or not met.. As such this whole category is rated at a lower level than some of the other more performance related characterizations. L() No votes. Fuel: N Clad: N Reactor: Y(1): PWR Burnup: N K(2): Data PK(3): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Oxygen content	Amount of oxide either dissolved or existing as an oxide phase in the cladding. H(2) Oxygen is a strong alpha stabilizer. Total amount of oxygen will affect phase equilibria. M(3) Data show low impact of initial oxide per se. Only Hydrogen related to the pre-transient oxide plays a role. This type of information is useful in explaining, and possibly extrapolating the observations, but does not represent direct confirmation that criteria are met or not met.. As such this whole category is rated at a lower level than some of the other more performance related characterizations, although the effect of oxygen content is one of the more important of the parameters in this category. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(4): Data, Judgement PK(1): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Fluence	****Fast neutron fluence experience by specimen H() No votes. M(2) At 62 GWd/t, the major factor is hydrogen pickup; however, the effect is less certain at higher burnups. This type of information is useful in explaining, and possibly extrapolating the observations, but does not represent direct confirmation that criteria are met or not met.. As such this whole category is rated at a lower level than some of the other more performance related characterizations L(3) Irradiation damages are quickly annealed during the transient. Second-phase precipitates are amorphized by irradiation, irradiation damages are annealed out rapidly at >550°C. Do not see how this will influence the result of the test. Fuel: N Clad: Y(1): Not well known for M5 and Zirlo. Reactor: N Burnup: N K(2): Data, judgement PK(3): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Determination of hydrogen and oxygen solubilities in α and β phases as a function of hydrogen, oxygen, and temperature for relevant alloys	Need definition H(4) These parameters are necessary to allow relevant modeling and analysis. M(1) seems to be redundant with establishing the phase diagram. Data directly influence assessment of the validity of the current LOCA embrittlement criteria for high-burnup operation and for new types of alloy. L() No votes. Fuel: N Clad: Y(1): More important for M5 and Zirlo Reactor: N Burnup: Y(1): More important at high burnup K(1): Data, judgement PK(4): Calculations, Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Determination of rate constants for rate-limiting transport mechanisms for phase transformation during heating as a function of hydrogen, heating rate and cooling rate	****Phase transformations often require atomic transport from one phase to the other, and atomic transport mechanisms often control the reaction rates. H(3) Should be known for relevant calculation and analysis. Knowing these transport mechanisms may allow the determination of reaction kinetics. M(1) Seems to be redundant with establishing the phase diagram. L(1) Alpha-to-beta transformation kinetics during the heatup phase are very fast. Beta-to-alpha transformation during the cooldown phase is not limited by cooling rate; that is, depending on cooling rate, either diffusionless martensitic transformation or transformation via nucleation and growth are possible. However, transformation microstructure and the degree of O and H redistribution during the transformation are strongly influenced by the cooling rate. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data, Judgement PK(3): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Motta comment: I think this is redundant with the previous item => propose we eliminate	Determination of diffusion coefficient of oxygen in individual phases	Need definition H(1) Drives the level of clad embrittlement. M(1) Seems to be redundant with establishing the phase diagram. L(1) A significant data base is available for Zr and Zircaloys. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data PK(1): Data, Judgement UK(): No votes.

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Waeckel comment: this item should be included in the fifth item of this list by adding *(heating and cooling phases)* after *temperature* in the definition.	Determination of the retained β and transformed β-phase morphology and oxygen plus hydrogen redistribution during β - α transformations (cooling), including Niobium-rich alloys	Need definition H(2) rated higher simply because this is the bottom line; other items are needed to develop an analytical representation. These factors play direct and very important roles which determine the clad resistance to thermal shock and the post-quench mechanical properties. M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(): No votes. PK(2): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Mechanical Properties at high temperature, e.g., ≥ 300 C (vote=10) Creep and burst tests Designed to investigate creep and burst behavior of cladding at high temperature	Specimen selection: Pre-existing oxide	Need definition H(1) Directly influences burst and creep strengths. M(2) Data show that impact is limited to related Hydrogen content and clad thinning. L(1) The pre-existing oxide thickness determines the remaining metal thickness which directly determines the creep and burst behavior. However, over the ranges of practical interest, the variations are not expected to be all that significant. Fuel: N Clad: N Reactor: N Burnup: N K(4): Data, Judgement PK(): No votes. UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Alloy and initial thermo-mechanical treatment	Need definition H(4) May affect the burst behavior. May impact the mechanical behavior . Data are needed to do relevant analysis. Creep behavior is known to vary significantly with thermo-mechanical treatment and alloy type. Clad temperature and phase stability are the most important factors. Initial thermomechanical treatment is a secondary factor M(1) Do not expect a big influence of cladding type. L() No votes. Fuel: N Clad: Y(1): More important for M5 and Zirlo. Reactor: N Burnup: N K(2): Data PK(2): Data, Judgement UK(1): No rationale provided.

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Hydrogen content	****Total amount of hydrogen in the material H(1) Affects burst behavior (alpha to beta transformation). M(4) Data show some hydrogen impact on the mechanical properties at high temperatures. The French have reported an effect of cladding creep strength with hydrogen content. Hydrogen content influence phase stability and burst behavior. Creep failure at <550C during a LOCA is of less concern. Do not expect a large effect. L() No votes. Fuel: N Clad: Y(1): Important for M5 and Zirlo Reactor: N Burnup: N K(1): Data PK(4): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Fluence (radiation damage)	Need definition H(1) Irradiation hardening is known to affect the cladding creep behavior. Alternate effects, such as precipitate dissolution, are not as well characterized. M(1) At 62 GWd/t, the major factor is hydrogen pickup; the importance at higher burnups is less certain. L(3) Irradiation damages are annealed at the test temperature. Irradiation damages are virtually annealed out rapidly at >600°C. Fuel: N Clad: N Reactor: N Burnup: N K(3): Data PK(2): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Strain profile as a f(r, θ, z, t)	****Measurement of local strain variation with strain gages and similar equipment, such that the full strain distribution is known. H(3) These data are used to validate the thermo-mechanical models. In the interest of creep deformation, an accurate history of the deformation behavior during the test is essential to characterize differences in behavior. Relative to burst behavior, characterization of the resulting burst strain may be sufficient without detailing temporal characterization. Difficult to obtain this data, but useful and with high importance if we can get it. M(1) Data are needed to develop models. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(3): Data, Judgement PK(1): Data, Judgement UK(): No votes.

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Pressure as f(t)	**** Internal pressure in the rod as a function of time. H(4) To be prototypical, the internal pressure should not be maintained constant during the clad ballooning phase (only the amount of moles of gas is constant) . To allow proper interpretation of the test, the internal pressure versus time should be measured. the creep deformation history cannot be interpreted without a corresponding temporal characterization of the driving force (pressure).. The preference would be that pressure be maintained constant during the test. M() No votes. L(1) Info is needed to develop models. Fuel: N Clad: N Reactor: N Burnup: N K(3): Data, Calculation PK(2): Data, Calculation, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Temperature as f(t)	Measurement of the time-varying temperature. H(5) Impacts mechanical resistances of the specimen. Phase transformation and distribution and subsequent cladding mechanical properties depend on the clad temperature. To use the tests results as a validation data base for the calculation codes, the time-varying clad temperature should be measured. Creep is a very sensitive function of the cladding temperature and therefore the temperature must be known. Burst and creep behaviors are sensitive to clad maximum temperature. Obviously need to know temperature. M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(4): Data, Calculation PK(1): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Temperature profile as f(θ) and f(z)	Measurement of azimuthal and axial variations of temperature. H(4) Phase transformation and distribution, and subsequent cladding mechanical properties, depend on the clad temperature. To use the tests results as a validation data base for the calculation codes, the time-varying clad temperature should be measured. Impacts mechanical resistances of the specimen. We should at least have some idea of the potential impact of the temperature variationsof the magnitude we expect. M(1) Burst strain is known to be sensitive to circumferential temperature differences. Measurement of the circumferential temperature distribution would be needed to best interpret the testing results. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(3): Data, Calculation PK(2): Data, Judgement UK(): No votes.

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Motta comment: I am not sure that the intent here was to use this as a substitute for biaxiality or to capture the fact that as the volume increases, the p decreases for closed end tube. This is what I will vote on	Conduct of Test-During Open (actively pressurized) or closed	**** The test is conducted either with closed ends tube (biaxiality factor = 0.5) or with open ends (biaxiality factor =0). H(3) It is crucial to represent the actual pressure evolution of a full-length rod. Knowledge and control of the internal pressure is essential to obtaining useful characterizations of creep and burst behavior which probably leads to open (actively pressurized) tubes. The pressure in a closed tube would vary with heatup and with cladding deformation. Affects test. M(1) Biaxiality can be included in the calculations. L(1) Closed burst is a better simulation. Fuel: N Clad: N Reactor: N Burnup: N K(4): Data, Judgement PK(1): Data, Judgement UK(): No votes.

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Waeckel Comment: should be included in the previous item	Conduct of Test-During Biaxiality ratio	****The state of stress experienced by the cladding during testing. H(3) There is preliminary information on the impact of axial stress on the cladding rupture; additional experimental results are needed. Burst at <830°C (deformation controlled by prism slip in the highly anisotropic alpha phase) is sensitive to biaxial ratio. Influences failure limit. M(1) The most directly useful testing would simulate the actual cladding stress state. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data PK(2): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-PTE Post-test strain (fractographic)	Need definition H(4) Relevant parameter. A key output of the burst characterization is the rupture strain, as input to flow blockage assessment. The most important test objective; needed to develop models. Fracture is predominantly ductile anyway; fractography is not important. Easy to do and useful. M() L(1) Relevance of the data is low especially is the internal pressure evolution is not prototypical Fuel: N Clad: N Reactor: N Burnup: N K(3): Data, Judgement PK(2): Data, Judgement UK(): No votes.

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Mechanical Properties at high temperature, e.g., ≥ 300 C (vote=10) Uniaxial test Designed to provide data for calculational codes **Waeckel comment: no need to repeat parameters already addressed in the creep-burst test subcategory (no change)**	Specimen selection: Alloy type and initial thermomechanical heat treatment	Composition or designation of the metal utilized in fuel-rod fabrication H(3) Basic mechanical properties have historically demonstrated significant differences as a result of thermomechanical processing (recrystallized vs. cold-worked stress relief-annealed) with smaller differences due to compositional variations. Basic mechanical properties have historically demonstrated significant differences as a result of thermomechanical processing (recrystallized vs. cold-worked stress relief-annealed) with smaller differences due to compositional variations. M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(1): Data PK(1): Data, Judgement UK(1): Judgement

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Waeckel comment: no need to repeat parameters already addressed in the creep-burst test subcategory (no change)	Specimen selection: Hydrogen content	Need definition H(3) Available properties measurements indicate that hydrogen content, at sufficient levels, can cause an increase in strength and decrease in ductility. The effect of prototypical hydrogen levels on mechanical properties is a item of considerable interest in this investigation. Tensile behavior at <500C is strongly influenced by hydride distribution. M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(1): Data, Judgement PK(2): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Waeckel Comment: no need to repeat parameters already addressed in the creep-burst test subcategory (no change)	Specimen selection: Oxygen content	Amount of oxide either dissolved or existing as an oxide phase in the cladding. H(1) Available properties measurements indicate that the metal oxide content can, in sufficient quantities, result in an increase in strength and a decrease in ductility. However, for the levels of oxygen content of practical interest (base-irradiated prior to high temperature oxidation), the oxygen effect result in only minor, if any, effects particularly relative to the cladding hydrogen content. Primary factor that influences tensile behavior. M(1) Data show low impact of initial oxide per se. Only Hydrogen related to the pre-transient oxide plays a role. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data PK(1): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Waeckel Comment: no need to repeat parameters already addressed in the creep-burst test subcategory (no change)	Specimen selection: Fluence	Need definition H(2) It has been well-established that the effect of irradiation (in the absence of other factors) is to increase the material strength and decrease ductility, but generally achieve a saturation effect relatively early in life. A primary area of lesser quantification, however, is in quantification of the effect of precipitate dissolution at elevated fluences. Primary material parameter at <550°C. M(1) At 62 GWd/t, the major factor is hydrogen pickup; the importance at higher burnups is less certain. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(1): Data PK(2): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Load and displacements, i.e., σ and ε behavior	****Determination of the stress-strain response of the material using uniaxial testing H(5) Objective of the test. The ability of the cladding material to withstand mechanical loadings is directly related to the basic mechanical properties; primarily ductility but also strength. Development of the material stress-strain curve provides information necessary to understand possible performance differences in the cladding capability with increasing exposure. Therefore, accurate measurement of these quantities is essential. Important for code development. M() No data. L() No data. Fuel: N Clad: N Reactor: N Burnup: N K(3): Data, Calculation, Judgement PK(2): Data, Judgement UK(): No data.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Waeckel Comment: should be included in previous phenomenon **Agree (ATM)**	Conduct of Test-During Total elongation, post-test	Need definition H(1) Total elongation is the primary measure of material ductility. Material ductility determines the ability of the material to resist or accommodate loadings without fracture. M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data PK(1): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Waeckel Comment: no need to repeat parameters already addressed in the creep-burst test subcategory (no change)	Conduct of Test-During Temperature and temperature rate	Measurement of the time-varying temperature. H(1) Impacts mechanical resistances of the specimen. Accurate measurement of isothermal test temperature is needed. M() No votes. L(1) These are mechanical property tests that should be performed under uniform and constant temperature. The primary consideration with heatup rate or time at temperature would be in the possible annealing of irradiation damage. It is expected that the temperatures and test times involved would not result in significant annealing of irradiation damage and therefore this is a lesser consideration. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data PK(1): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Waeckel comment: no need to repeat parameters already addressed in the creep-burst test subcategory (no change)	Conduct of Test-During Strain rate	Need definition H(2) Relevant parameter. Primary test parameter to be fixed and measured. M(1) Available testing has demonstrated that strain-rate effects exist. However, for the purpose of tensile property testing, the strain rate should be relatively quick (to best reflect true elastic-plastic behavior and avoid creep-induced inaccuracies), and within the practical range of achievable test strain rates relative to the target, spurious strain rate effects are not expected. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data PK(1): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Waeckel comment: Not clear: what is the issue? **Potts has same question**	Conduct of Test-During Circumferential (hoop)/axial (not ring)	****Whether the uniaxial test should be done by a ring test or by an axial test H(2) Relevant for non-isotropic materials. Primary test parameters to be measured. M(1) Appropriate test should be used L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data PK(1): Data, Judgement UK(): No votes.

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Category D– Separate Effect Testing

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Mechanical Properties at high temperature, e.g., ≥ 300 C (vote=10) Post oxidation and quench ductility test	**Action Item:** **Propose and justify the type of test(s), e.g.,** **1. Axial tensile** **2. Ring tensile** **3. Ring compression** **4. Impact** **5. Bending**	****To simulate a post LOCA seismic event 2 types of mechanical tests are suggested: - Four-point bending test. The specimen should be a least 50 cm long (one span) and should contain its gap closed fuel pellet stack. The loading to be applied to the specimen should be limited to a given deflection (during a seismic event the maximum deflection for a 4 m fuel assembly is currently less than 25 mm) - Impact test to simulate the impact between the grid dimples and the rods. The specimen should be 5 to 10 cm long and should include its fuel pellet stack. The loading is a pulse whose magnitude and width are respectively 165 N and 2-3 ms H(4) In order to get immediately comparable data to those from which the criteria were deduced in 1973, perform the new test with a ring compression process. Ring tensile tests may be very severe (recent Halden results on dried-out rods). the relevance of the mechanical test is the key. The loading applied to the specimen should be prototypical. It is imperative that the right type of testing be performed to determine the most relevant characterization. The best testing to perform is four-point bend testing, supplemented by ring testing. Four point bend testing directs addresses the post-LOCA performance limit of greatest interest, while ring testing provides supplementary insight into the fundamental mechanical properties as and aid in interpretation of the four-point bend testing results. The order of higher importance is--impact test followed by ring-compression test. These types of test are most applicable to post-quench modes of loading (due to various hydraulic, handling, and other mechanical forces) and deformation of the ballooned, burst, and oxidized cladding. Bending test is addressed in separate below (i.e., ability to withstand post-LOCA seismic events and aftershocks). M(1) Axial tensile test is a convenient test that can identify the most vulnerable spot along the cladding length, however, post-quench axial tensile loading is not expected to occur or to be insignificant in magnitude. Test results should be interpreted very carefully, because according to previous studies in ANL and JAERI, the most vulnerable spot produced in burst cladding is strongly influenced by the selected heating method, the degree of temperature nonuniformity near the burst region, and oxidation and hydrogen uptake from the clad inner surface. L(1) Ring-tensile stress in a burst cladding is either negligible or insignificant in post-quench phase. Fuel: H

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PWR and BWR LOCA
Category D– Separate Effect Testing

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Seismic tests Test type: 4--point bending Separate effect test that addresses the ability of the fuel rod to withstand a post-LOCA seismic event without shattering	Specimen selection: Alloy type	Composition or designation of the metal utilized in fuel-rod fabrication H(4) May affect oxygen distribution and hydrogen pickup. Hydrogen pick-up fraction of the alloy during operation will be a primary parameter since very little hydrogen is absorbed during the LOCA transient. Very little, if any, of this type of testing has been performed to date and therefore a judgement of the relative importance of various parameters is difficult and necessarily speculative at this time. It is proposed for this category that all identified parameters be assigned High Importance but Unknown. The effects of O, H, hydrides, and the microstructure of prior beta layer are strongly influenced by alloy type. M() No votes. L() No votes. Fuel: N Clad: Y(1): More important for M5 and Zirlo Reactor: N Burnup: N K(1): Data PK(1): Data, Judgement UK(2): Lack of data

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Thickness and morphology of pre-existing and transient oxides	****The total amount of oxide formed on the cladding and whether the oxidation is uniform or nodular, and whether there is extensive cracking and spalling. H(3) Oxide related clad thinning will slightly affect the mechanical behavior of the cladding. Very little, if any, of this type of testing has been performed to date and therefore a judgement of the relative importance of various parameters is difficult and necessarily speculative at this time. It is proposed for this category that all identified parameters be assigned High Importance but Unknown. These parameters strongly influence the thickness, O and H contents, and hydriding behavior of the load-bearing prior beta layer. M(1) No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(3): Data, Calculation PK(): No votes. UK(1): Lack of data

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PWR and BWR LOCA
Category D– Separate Effect Testing

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Burnup	Need definition H(2) Very little, if any, of this type of testing has been performed to date and therefore a judgement of the relative importance of various parameters is difficult and necessarily speculative at this time. It is proposed for this category that all identified parameters be assigned High Importance but Unknown. Major factor that influences the material structure and properties. M(1) At 62 GWd/t, the major factor is hydrogen pickup; however, the importance at higher burnups is unclear. L(1) The irradiation damages have been annealed during the LOCA transient and will not affect the post-LOCA mechanical behavior of the cladding. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data, Judgement PK(1): Data, Judgement UK(1): Lack of data

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PWR and BWR LOCA
Category D– Separate Effect Testing

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Pre-existing and transient hydrogen content and distribution	Amount and distribution of pre-existing hydrogen associated with fuel rod clad segment. This hydrogen may be in solution in the metal or may exist combined with the metal as a discrete hydride phase. H(4) Affects oxygen solubility in the beta phase and post-quench ductility. Since little Hydrogen is absorbed by the cladding during the LOCA, the initial Hydrogen content will play a key role during the post-LOCA mechanical tests. The initial Hydrogen distribution has no importance. Very little, if any, of this type of testing has been performed to date and therefore a judgement of the relative importance of various parameters is difficult and necessarily speculative at this time. It is proposed for this category that all identified parameters be assigned High Importance but Unknown. Post-quench hydride distribution is the major factor that influences the mechanical properties, especially at <200°C. M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data, Judgement PK(1): Data, Judgement UK(1): Lack of data

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: With or without ballooning	Need definition H(4) Ballooning affects the mechanical resistance due to internal hydriding by stagnant steam. The clad geometry change (clad thinning and diameter increase) will affect the mechanical behavior of the rod. The real issue is away from the ballooned section; it is already recognized that the ballooned section is mechanically compromised, may lose it's fuel material, and that additional damage during the seismic event may occur. It would probably be of interest to characterize this secondary damage, but mechanical fracture of that region has already occurred. The unanswered question is whether the seismic loads will cause unacceptable failure elsewhere. Ballooning and burst influence strongly clad ID-side oxidation, hydrogen uptake, and hydriding, producing weak spots near the burst opening. M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(1): Data, Judgement PK(2): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Temperature	Measurement of the time-varying temperature. H(3) Ductility may vary a lot with temperature. Variations in performance with test temperature have been demonstrated by Hobson's ring tests. The more critical issue is to define the relevant temperature range, and then maintenance of that temperature during the test should be achievable and enforced. With the extent of embrittlement anticipated in the test sample, the maintenance of the intended temperature range is critical for obtaining meaningful test results. Bending temperature (<200°C) is a major factor that influences test results. M() No votes. L(1) The post LOCA tests are isothermal. Fuel: N Clad: N Reactor: N Burnup: N K(): No votes. PK(4): Data, Experience, Judgement UK(): No votes.

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Strain rate (displacement ratio)	**** Measurement of the strain versus time H(3) Relevant parameter. The objective of the test is to measure the response of the rod to an imposed deflection. Strain rate effects can be expected; prototypical strain rates are needed to ensure meaningful test results M(1) No rationale provided (ANL) L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(): Data PK(3): Data, Judgement UK(): No votes.

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Potts comment: Seeks clarification of what was intended.	Conduct of Test-During ASTM specification	**** The shape of the contact points and the way to apply the loading should follow the ASTM specification to avoid undesirable experimental artifact (local stress concentration) H(2) Relevant specification to avoid non-prototypical loading of the rod. M(1) It may be difficult to apply it for ballooned, burst, and nonuniformly oxidized and hydrided cladding. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(1): Data PK(3): Data, Calculation, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Appropriate bending moment	**** During a seismic event the fuel assembly is submitted to a prototypical bending moment . H(4) The tests have to be prototypical.. The loading to be applied to the specimen should be limited to a given deflection (during a seismic event the maximum deflection for a 4 m fuel assembly is currently less than 25 mm). The application of an appropriate bending moment is essential to obtaining meaningful results. However, it is also anticipated that once the protypical bending moment is demonstrated to be successful, the bending moment will be increased to determine margin to the critical bending moment for failure and whether the consequences of failure are truly unacceptable from the consideration for maintenance of coolable geometry. M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(1): Data, Judgement PK(3): Data, Calculation, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Cycling	**** Apply a cyclic loading on the rod to simulate the seismic event. H(3) Cycling induces metal fatigue. By the very nature of the post-LOCA seismic event, cycling can be anticipated, although at a relatively low frequency. It is well-known from fatigue studies that the allowable strain amplitude decreases with increasing number of cycles; the quantification of this reduction would be needed if it appears that the expected loading approaches the level for unacceptable consequences with a single cycle. However, if considerable margin to fracture/unacceptable consequences exists then multiple cycle testing may not be necessary. M() No votes. L(1) The magnitude of the seismic load is low enough to avoid plastic deformation of the clad and the number of cycles is not large enough to create fatigue damage. No cumulative damage is expected. Fuel: N Clad: N Reactor: N Burnup: N K(1): Data, Judgement PK(3): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-PTE Characterize integrity	**** Define the level of fragmentation of the cladding after the post-LOCA mechanical test. H(4) The objective of the test is to define the LOCA limits (%ECR and max clad temperature) that provoke clad fragmention and potential subsequent core coolability concern by allowing extended fuel dispersal. These limits are beyond those leading to a simple loss of clad integrity. Characterization of post-test geometry is critical to the determination of whether an acceptable geometry has been maintained (when demonstrating the prototypical bending load case), or whether a truly unacceptable condition is developed with fracture (when the test is extended to intentionally develop fracture).. M() L() Fuel: N Clad: N Reactor: N Burnup: N K(1): Data, Judgement PK(1): Data, Judgement UK(2): Lack of data

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-PTE Characterize local hydrogen	Amount and distribution of hydrogen associated with fuel rod clad segment. This hydrogen may be in solution in the metal or may exist combined with the metal as a discrete hydride phase. H(4) Primary parameter that could impair the clad resistance. Only the initial amount is important. The Hydrogen distribution has no impact since it becomes uniform during the LOCA transient. A characterization of the hydrogen and oxygen distribution would aid in the interpretation of the test results. The fracture characteristics and susceptibility are expected to be directly related to these embrittling agents. Hydride morphology, orientation, number density, and distribution influence test result significantly. M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: Y(1): More important at high burnup K(1): Data PK(2): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Simulation of fuel relocation Take a high burnup rod, balloon and burst the rod, and determine the fuel relocation and posttest thermal conductivity	Specimen selection: Burnup	The amount of burnup to which the fuel rod used for the specimen was exposed. H(4) Fuel morphology (fragmentation, rim characteristics, bonding, etc.) are important. The nature of the bonding between the pellet and the cladding changes with the burnup increase. It will affect the potential for fuel relocation. The segment burnup level can determine the extent of pellet-cladding bonding and corresponding susceptibility to fuel relocation during ballooning and rupture. Fuel and rim-zone microstructure and the state of bonding with cladding are strongly influenced by fuel burnup. M() No votes. L() No votes. Fuel: Y(1): MOX agglomerates Clad: N Reactor: N Burnup: N K(1): Data PK(3): Data, Judgement UK(): No votes.

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Fuel type (MOX)	Need definition H(2) May affect the amount of fine grain material after relocation. Fuel structure and mechanical properties are influenced by fuel type. M(1) The consequence of fuel fragments relocation (higher local decay heat and higher cladding temperature) could be more effective with MOX fuel than with UO2 fuel. Nevertheless the viscoplastic properties of the MOX should impair the fuel fragments relocation at high burnup. L(1) No significant differences in pellet-cladding bonding behavior or pellet cracking behavior are anticipated or have been observed with MOX fuel, and therefore no significant differences in relocation behavior are anticipated. Fuel: N Clad: N Reactor: N Burnup: N K(1): Data PK(2): Data, Judgement UK(1): Judgement

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Alloy type	Composition or designation of the metal utilized in fuel-rod fabrication H(2) May affect burst (beta favoring or alpha favoring additions). Ductile burst and brittle failure by thermal shock and post-quench forces are influenced strongly by cladding alloy type. M(1) In general, compositional differences have not been observed to significantly affect cladding burst behavior. However, if significant differences in burst behavior occurred, the relocation characteristics could be similarly significantly altered. L(1) Data show no significant impact of alloy type on the balloon size that could influence the fuel fragments relocation. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data PK(1): Data, Judgement UK(1): Judgement

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Chemical and mechanical bonding	***** Chemical and mechanical bonding between the fuel pellet and the cladding.* H(4) Fuel morphology (bonding) is important. It will affect the potential for fuel fragmentation relocation. It is speculated that bonding could significantly affect the relocation characteristics by impeding pellet fragment movement. However, this effect has not been demonstrated. Major factor that influences fuel slumping and potential release of fuel particles upon burst and subsequent fragmentation. M() No votes. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(): No votes. PK(3): Data, Judgement UK(1): Lack of data

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen selection: Cracking	**** Crack pattern and crack density of the fuel pellets prior to the test. H(2) Controls the ruffle bed characteristics after relocation. Degree of fuel cracking directly influences the potential for fuel relocation and release. M() No votes. L(2) Beyond a given burnup the number of cracks is stable. In general the macroscopic fuel pellet cracking pattern develops early in life and does not change significantly with elevated exposures. Therefore, this contribution to fuel relocation susceptibility is not expected to be a dominant parameter during this test series. Fuel: N Clad: N Reactor: N Burnup: N K(1): Data PK(3): Data, Judgement UK(): No votes.

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During With or without blowdown	Need definition H() No votes. M(1) During the blowdown phase of the LOCA transient, there is much less heat generation in the fuel and the clad coolant heat transfer is drastically reduced. Therefore, it is observed that the fuel stored energy is redistributed in the pellet and the clad. This redistribution produces a decrease of the pellet center-line temperature and increases the pellet rim and clad temperatures. Due to these temperature transients, the central part of the pellet will suffer a contraction while the rim and the clad will experience an expansion. Fuel mechanical stresses and fragmentation could be induced by these adverse effects. Bonding and fuel debris sizes may be affected by the expansion and contraction inside the fuel pellet. L(2) This aspect may relate to the vibrational loads that occur during the blowdown phase and may cause additional pellet fragment movement at the initiation of the event. In general, pellet fragments are relatively constrained within the fuel rod by the column geometry, as evidenced by characterization of fuel column geometry after shipping to hotcells for examination. Therefore, this effect is not considered to significantly contribute to relocation susceptibility later during the cladding heatup and rupture phases. The other possibility is the fuel thermal contraction and cladding heatup during the blowdown phase that thereby increases the pellet-cladding gap and possibly facilitates pellet fragment relocation in this manner. In this case, again this is not significantly different from the gap change that occurs on cooldown and is observed to not significantly increase any apparent fuel fragment relocation, especially in high exposure fuel. Cladding heatup rate and temperature, either with or without a blowdown, are the primary factors that influence burst shape and dimensional changes. Fuel: N Clad: N Reactor: N Burnup: N K(): No votes. PK(1): Data, Experience, Judgement UK(2): Judgement

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Blowdown temperature transients for fuel and cladding	Need definition H(2) Important parameters that influence cladding burst and dimensional changes. M() No votes. L(1) This aspect may relate to the vibrational loads that occur during the blowdown phase and may cause additional pellet fragment movement at the initiation of the event. In general, pellet fragments are relatively constrained within the fuel rod by the column geometry, as evidenced by characterization of fuel column geometry after shipping to hotcells for examination. Therefore, this effect is not considered to significantly contribute to relocation susceptibility later during the cladding heatup and rupture phases. The other possibility is the fuel thermal contraction and cladding heatup during the blowdown phase that thereby increases the pellet-cladding gap and possibly facilitates pellet fragment relocation in this manner. In this case, again this is not significantly different from the gap change that occurs on cooldown and is observed to not significantly increase any apparent fuel fragment relocation, especially in high exposure fuel. Fuel: N Clad: N Reactor: N Burnup: N K(1): Data, Judgement PK(2): Data, Experience, Judgement UK(): No votes.

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Potts comment: I'm not sure what this is. It may be to characterize the amount of fuel relocation that occurs after/during ballooning but prior to burst. This would be useful to understand the relocation mechanism which is at the moment speculated to be a result more of the gas flow on perforation rather than simple gravity-induced motion.	Conduct of Test-During Pre- and post-burst test phases (2)	**** Look at the impact of the fuel fragments relocation on the cladding temperature during the high temperature oxidation phase and the quenching phase. H(1) Data of fuel relocation determines the impacted phases. M(3) Needs in pile test to be prototypical (heating source should come from the fuel). If the objective is as speculated above, this test would help to characterize at which point in time the bulk of the relocation occurs. However, most rods that balloon also burst and it is not clear that a separation in time would significantly affect the LOCA performance (i.e., whether relocation occurs instantaneously to fill the ballooned region as opposed to instantaneous relocation on burst). Burst shape and dimensional changes are influenced by clad phase at the time of ballooning and burst. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(1): Data, Judgement PK(3): Data, Calculation, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Internal pressure and moles of gas	The amount of gas in the rod upper plenum, for a given initial pressure in the test rod. H(3) Driving force for relocation, together with gravity. It is crucial to have a pressure evolution representative of a full-length rod. Internal gas pressure is the driving force for fuel fragments relocation. To be prototypical the amount of gas within the rod prior to the test has to be maintained constant. The internal pressure is a measured parameter, not an input data. Initial pressure is the primary factor that determines the burst temperature and shape and potential release of fuel particles from rim zone at burst. Plenum gas inventory is a secondary factor. M(1) If gas flow is the primary relocation mechanism, then an accurate simulation of that gas flow would be needed to obtain the most meaningful results. However, it is anticipated that similar relocation behavior would be obtained over a relatively wide range of gas flows. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(): No votes. PK(4): Data, Calculations, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Flow induced vibration	During ballooning and after burst, the fuel rod vibration induces by the flow can favour the fuel pellet stack crumbling. H() No votes. M(2) Fuel column axial gaps have been observed to form and continue during normal reactor operation. This results suggests that fuel column shakeout is not likely with normal flow-induced vibration even over very extended periods. It is further noted that with cladding perforation, steam ingress will promote fuel pellet oxidation that has been observed, with failed fuel during normal reactor operation, to cause effective blockage within the fuel rod to preclude fuel downward fuel pellet fragment motion, again overriding the effects of flow induced vibration. Secondary driving force. L(2) Potential impact of rod vibration is expected to be small. Ballooning and burst occur after blowdown, and steam-flow-induced vibration during and after blowdown would be insignificant. Fuel: N Clad: N Reactor: N Burnup: N K(): No votes. PK(2): Data, Judgement UK(1): Judgement

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Waeckel comment: should be removed	Conduct of Test-During Exterior rod constraints	Need definition H(1) Prior ballooning experiments have shown that coplanar ballooning is not likely, and therefore balloons may not be constrained by adjacent ballooned sections. However, the constraints provided by adjacent non-ballooned rods can still provide a significant restriction on the amount of cladding ballooning and corresponding fuel relocation. M(1) Rod constraints during ballooning may affect the fuel distribution at the relocation site. L(2) The purpose of these tests is to analyse the separate effect of fuel fragment relocation. Exterior constraints influence ballooning shape to some extent. Fuel: Y(1): Most modern BWR fuel designs use part-length fuel rods resulting in zones where there is a significant gap between adjacent rods (because rods in certain lattice locations terminate at a lower elevation). This design feature may permit greater ballooning and relocation at those elevations. However, the fuel rods at those peculiar locations would correspondingly experience a circumferential temperature gradient, which is known to reduce the resulting burst strain. Clad: N Reactor: N Burnup: N K(): No votes. PK(4): Data, Judgement UK(): No votes.

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Balloon size and burst size	Need definition H(4) Affects the amount of relocated fuel in the balloon. The balloon and burst size represents the maximum potential volume for relocation. Directly influence the potential for fuel relocation, slumping, and release at and after burst. M() No votes. L(1) Balloon size and burst size are measured after the test. No need to measure it on-line Fuel: N Clad: N Reactor: N Burnup: N K(1): Judgement PK(2): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-During Length	Longitudinal dimension of the fuel rod segment to be tested. H(2) The driving force for fuel fragments relocation is the internal gas pressure in the plenum.. For high burnup fuel rods the axial gas transport is significantly impaired. A short rod would favour the plenum gas participation The rod length has to be prototypical to avoid experimental bias. At the least, the length between two grids must be tested. M(1) The amount of fuel above the ballooned/burst section defines the potential fuel volume to be relocated. However, the size of the ballooned/burst region defines the maximum possible relocated fuel volume. Therefore, if the ballooned/burst location can be defined with reasonable certainty, sufficient length can be provided above that region to enable prototypic relocation. L(1) Length more than about 15 times of the pellet length (6 inches) is sufficient. Fuel: N Clad: N Reactor: N Burnup: N K(1): Calculation PK(3): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-PTE Granularity of dispersed material	**** Granularity of dispersed fuel fragments is measured to get relevant information on the fuel density in the relocated fuel fragments zone. H(3) The equivalent fuel density of the relocated fragments allow codes to simulate the local overheating of the cladding. Major factor that influences the potential for fuel relocation and release. M(1) Smaller pellet fragments would be expected to result in easier fuel movement and possibly a higher density of relocated fuel. However, pellet cracking patterns are established early in life and do not vary greatly with increased exposure, so a widely varied granularity of material, prior to dispersal, is not expected. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(): No votes. PK(4): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Waeckel Comment: should be an on-line measurement of the impact of fuel relocation on cladding temperature	Conduct of Test-PTE Thermography	Need definition. H(1) Provides the fuel distribution in 3D. M() No votes. L(2) Low added value Fuel: N Clad: N Reactor: N Burnup: N K(): Data PK(2): Data, Judgement UK(1): Judgement

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Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
Waeckel Comment: should be included in *granularity of dispersed material* (see above). The objective is the same	Conduct of Test-PTE Thermal diffusivity of rubble bed	Need definition H(1) Output parameter. M(1) Probably difficult to do, but would be useful in quantifying the effective thermal properties of the rubble mass (I'm assuming in the ballooned/burst region if the material is still there – you probably want to capture this just prior to burst although there may not be significant relocation at that time if gas flow is the primary relocation mechanism), otherwise this is best done analytically. L(1) No rationale provided. Fuel: N Clad: N Reactor: N Burnup: N K(): No votes. PK(2): Data, Judgement UK(1): Judgement

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-PTE Strain profile of cladding as f(r,z)	**** Measure the shape and the size of the ballooned area of the tested fuel rod.) H(3) The purpose of this test is to assess the amount and characteristics of relocation. A determining aspect of that process is the amount of ballooning (free volume to which the fuel may relocate), and therefore this volume should be known in any assessment of relocation characteristics. Note that the circumferential variation of cladding strain should also be determined. Axial variation of clad circumferential strain is a parameter that directly influences the potential for fuel relocation and slumping. M(1) Will give some indications on potential impact of the balloon the shape (magnitude and extension) on the amount of relocated fuel. L() No votes. Fuel: N Clad: N Reactor: N Burnup: N K(1): Judgement, Calculation PK(3): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-PTE Burst size	**** Size of the opening in the cladding after the burst. H(3) This is taken to be the effective surface area of the bulged region that was removed as a result of the burst. Similar to the preceding item, this hole siae will be a determining factor in the amount of relocated fuel retained within the ballooned region. Burst opening size and burst circumferential strain are the parameters that directly influence the potential for fuel relocation and release at and after burst. M() No votes. L(1) If the internal pressure is not maintained (prototypal case) the opening is small. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data PK(2): Data, Judgement UK(): No votes.

Subcategory (Test type)	Phenomena (Parameter)	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Conduct of Test-PTE Material balance (in-rod and dispersed)	Need definition. H(2) This is the primary result to be quantified in this test series, to be correlated with the ballooned region and burst size. It is the amount of lost material that is of interest as it could possibly contribute to such effects as flow blockage, etc. M() L(2) This information is covered by the local measurement of the fuel density. Fuel: N Clad: N Reactor: N Burnup: N K(1): Judgement PK(2): Data, Judgement UK(1): Judgement

APPENDIX E

EXPERIMENTAL DATABASES

The experimental databases identified in Section 4 of this report are further discussed below. The author of each contribution is identified. The contributed documentation exhibits some style differences. References providing additional details for each test program are provided at the end of each contributed entry.

E-1. Separate Effect Tests

Cladding Mechanical Properties Tests (United States)

The information regarding this test series was provided by panel member A. Motta of the Pennsylvania State University and M. Billone of Argonne National Laboratory.

Argonne National Laboratory (ANL) and the Pennsylvania State University (PSU) are working together on a NRC-funded program to investigate cladding properties and to test LOCA acceptance criteria at high burnups. Although the main focus of the program is to investigate fuel behavior under LOCA conditions, related mechanical properties testing is being done under both LOCA conditions and RIA conditions. The tests at relatively low temperatures and high strain rates appropriate for RIA conditions are described briefly here. The objectives are two-fold: to understand the degradation in cladding failure behavior at high burnup and to obtain stress-strain relationships that will serve as inputs to codes. High-burnup fuel rods (about 70 GWd/MTU) from the H. B. Robinson PWR are expected to be available for these tests along with related archive fresh tubing. Although the fuel has not arrived at the time of this writing, high-burnup specimens (about 50 GWd/MTU) from TMI-1 are available and have been used for preliminary testing along with unirradiated Zircaloy-4 tubing.

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Similar testing will be done on axial tensile specimens electromachined from de-fueled portions of irradiated fuel rods and from unirradiated tubing specimens. These tests will be performed over the same temperature range and strain-rate range as the ring-stretch tests mentioned above. The combination of the axial and the hoop stress-strain properties will allow validation and improvement of the models used in fuel rod codes for predicting the mechanical behavior of an anisotropic alloy such as Zircaloy.

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Biaxial tube burst tests are the most informative and the most difficult to perform, and they consume the largest amount of specimen material, which is a significant consideration when testing irradiated fuel material. These tests will be done in a more limited temperature range of 300-400°C, but they will explore the effects on deformation and failure of stress biaxiality ratios from 1:1 to 2:1 at high strain rate. In principle, the tests can be run with the fuel intact or with the fuel removed. Some tests will be run with the fuel removed to generate baseline data for code validation along with data that can be compared to other such studies on unirradiated and medium-burnup cladding.

<u>References</u>

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2. The calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before steam oxidation.

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Material Condition	Fuel Rod ID	Grid Span (Location from bottom in mm)	Test Time in Terms of Calculated ECR	Post-Test Examinations
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		6 (70-370)	>30%	M, O, P, F
	J4	6 (70-370)	17%<ECR<30%	M, O, P
		5(70-370)	TBD	TBD
	J6	6(70-370)	TBD	TBD
		5(70-370	TBD	TBD
Archive	---	---	17%	M, O, P
			17-30%	M, O, P
			>30%	M, O, P, F

(All tests are to be run at a peak cladding temperature of 1204_C; TBD = to be determined, M = metallography, O = oxygen analysis, H = hydrogen analysis, P = profilometry, F = fractography)

Cladding Mechanical Property Tests (Japan)

Ductility reduction due to hydrogen absorption and neutron irradiation was investigated for BWR cladding using the uniaxial tensile test many years ago, though both the hydrogen concentration and neutron fluence were much lower than the level currently of interest for high burnup fuels. Except for the general post-irradiation examination, BWR cladding has not been tested in recent years. Less significant corrosion and hydrogen pick-up than occurs in high burnup PWR fuel are an important factors is this situation. However, ductility reduction in BWR cladding is possible in the expected high-burnup range. Thus, mechanical property tests are planned. JAERI is interested in the morphology and the distribution of hydrides that are specific to BWR cladding. Tube burst tests for hydrided claddings are planned.

E-2. Integral Tests

BWR Transient Dryout and Rewet Tests

The ATWS instability and the LOCA have been identified as key events for the evaluation of fuel performance for a BWR. In ATWS instability the BWR will be at low flow for natural circulation and experience power oscillations. During these oscillations the high power fuel bundles may undergo periodic boiling transition and rewet following each power pulse. As long as the PCT remains below the minimum film boiling temperature, rewet will occur and excessive fuel heat up is avoided. However, if the cladding temperature exceeds the minimum film boiling temperature (approximately 600 ^{0}C (1100 ^{0}F)) following a power pulse the fuel may not rewet and substantial fuel heat up can occur.

Data for transient dryout, post dryout heat transfer and transient rewet have been obtained since the mid sixties. The data include simple geometry tests as well as full scale simulated fuel bundles.

Simple geometry data[1,2,3] have typically been obtained in tubular and annular geometries and include steady state as well as transient tests. These tests typically give well defined thermal hydraulic data and are excellent for model qualification. They do, however not provide information on the cross sectional variation of thermal hydraulic conditions in a rod bundle. The maximum peak cladding temperature (PCT) for these tests goes well beyond the minimum film boiling temperature, where rewet is not obtained. These tests therefore provide valuable information on boiling transition, film boiling heat transfer and rewetting.

Similar tests have been obtained in simple rod bundles,[4,5,14] typically 4X4 rod bundles. In these tests both steady state and transient tests have been performed. The steady state test were used to obtain information on film boiling heat transfer, while the transient tests were used to obtain additional information on transient dryout and rewet. The transients were either simple power and flow transients where either the power was temporarily raised or the flow temporarily reduced to obtain a boiling transition, or they were simulation of a reactor turbine trip or recirculation pump trip. These tests also give PCTs beyond the minimum film boiling temperature and provide valuable information on boiling transition, film boiling heat transfer and rewetting.

BWR fuel vendors perform extensive critical power tests for each new fuel product that is developed. Steady state critical power data over a range of parameters covering normal steady state operation as well as the expected range of parameters for operational transients. These data are used to develop a fuel type specific critical power correlation. In addition a few transient tests are usually performed in order to demonstrate the applicability of the correlation under transient conditions.[6,7,8,11,19,27,28,29,30,31] The transient tests are simulated turbine trip and recirculation pump trip transients, and in one instance a reactor instability was simulated. Since the transient tests are intended to demonstrate the applicability of the critical power correlation under transient conditions, the PCT typically does not exceed the saturation temperature by more than 100-200 ^{0}C and thus does not provide data beyond the minimum film boiling temperature.

Numerous loss of coolant accident (LOCA) experiments have provided information on transient dryout, film boiling heat transfer and transient rewet. These tests include data from the BDHT,[15] TLTA, [16] FIST, [17,18] FIX, [9,10,21,22,23] TBL, [24] and ROSA-III[25,26] test facilities, which are all scaled simulations of BWRs. The upper range of PCTs for these tests is approximately 870 ^{0}C (1600 ^{0}F). High temperature data up to 1150 ^{0}C (2100 ^{0}F) have been obtained in GE's core spray heat transfer test facility and from the GOTA test facility and similar facilities at Hitachi and Toshiba.[20]

Finally in-pile test have been performed, where nuclear fuel rods have been subject to boiling transition during power and flow transients. Even though the primary purpose of these tests was to evaluate the thermal and mechanical response of the fuel, these tests also provide valuable data on transient dryout and rewet. The early data in the van Houten report[13] were collected for exposures up to 20 GWd/t and peak cladding temperatures up to 1700 ^{0}C. The later data from the Halden test reactor[13] had exposures up to 40 GWd/t and peak cladding temperatures up to 950 ^{0}C.

The transient dryout and rewet tests are summarized in the table that follows the references.

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Transient Dryout and Rewet Tests.

Geometry	Test Type	PCT	References
Simple Geometry Tests			
Tubular and Annular	Steady State and Transient	850 °C	1, 2, 3

Simple Rod Bundles			
4X4 Rod Bundles	Steady State Film Boiling Flow and Power Transients Simulated Turbine and Pump	715 ^{0}C	4, 5, 14
Full Scale Rod Bundles			
	Simulated Turbine and Pump Trips for 8X8, 9X9 and 10X10 Rod Bundles		6, 7, 8, 11, 19, 27, 28, 29, 30, 31
LOCA			
Scaled Simulation of a BWR.	BDHT, TLTA, FIST, FIX, TBL, ROSA	870 ^{0}C	9, 10, 15, 16, 17, 18, 21, 22, 23, 24, 25, 26
Core Spray Heat Transfer	CSHT, GOTA. Toshiba, Hitachi	1150 ^{0}C	20
In-Pile Data			
	Flow and Power Transients	1700 ^{0}C	12, 13

Note: Minimum Film Boiling Temperature 600 ^{0}C.

Dryout Effects on High Burnup Fuel (OECD Halden Reactor Project-Norway)

The information regarding this test series was provided by panel-member W. Wiesenack.

Background

The objective of the dry-out test series was to provide information on the consequences for fuel of short-term dry-out incidents in a BWR. The experimental method employed was, on an individual basis, to expose fuel rod with different burnups to single or multiple dry-out events; to follow this by either unloading or continued operation in the reactor; and to finish with post irradiation examination and testing with emphasis on fuel clad properties. The test series was co-sponsored by the Halden Project's joint program and TEPCO (Japan).

Testing program

The test series comprised three loadings of IFA-613. Each rod was contained in a stainless steel channel within the rig so that the coolant conditions for each rod could be controlled individually. In this way separate dry-out scenarios were effected for each rod. Thermocouples attached to the surface of the test rods were used to monitor clad surface temperature and clad elongation was monitored by way of an extensometer. The first and second loading operated for a month after dry-out whilst the rods in the last loading were unloaded directly after the dry-out procedure. In neither case did any fuel failures develop.

The in-pile dry-out experiments with the third (and last) set of fuel rods in IFA-613 were completed in January '98 (HWR-552, HP-1036) and the post irradiation examination

(PIE) on all eight rods in the three test series were finished in September '98 (Kjeller hot cell).

Summary of results

In total, 2 rods with fresh Zr-2 and Zr-4 and 6 rods with clad pre-irradiated to 22-40 MWd/kg (Zr-2, Zr-2 with liner and Zr-4) were individually exposed to reduced or no-flow conditions in a heated light water loop within the Halden reactor. Dry-out occurred over the upper region of each rod, with 6 rods developing peak clad temperatures in the range 950-1200°C occurred in the other two rods.

An overview of the condition of the rods in terms of clad surface condition, rod dimensions and hydriding was achieved using non-destructive PIE techniques such as profilometry and neutron radiography. Clad and fuel microstructure and clad mechanical properties were investigated with destructive PIE techniques including ceramography, metallography, microhardness and ring tensile testing. It was observed that whilst dry-out had not affected the fuel microstructure, significant changes had been induced in the clad. These included high temperature corrosion resulting in moderate growth of the outer surface oxide layer and H_2 pick-up (hydriding formation). Some of the rods also exhibited uniform and localised clad creep-down into pellet-pellet interfaces and in the most severely tested rods that clad had undergone the α to β phase transformation. This material exhibited reduced UTS and brittle fracture. However, significant improvements of ductility were observed in clad that had been exposed to less severe in-pile transients where a small α-phase grain structure was retained and hydrogen pick-up was minimal. None of the rods failed, neither during the dry-out phase or the following steady-state normal operation.

Applications

The data obtained will be used to assess and modify existing rules/regulations in member countries on the continued operation with fuel elements subjected to short-term dry-out transients in boiling water reactors.

APPENDIX E

EXPERIMENTAL DATABASES

The experimental databases identified in Section 4 of this report are further discussed below. The author of each contribution is identified. The contributed documentation exhibits some style differences. References providing additional details for each test program are provided at the end of each contributed entry.

E-1. Separate Effect Tests

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BWR Transient Dryout and Rewet Tests

The ATWS instability and the LOCA have been identified as key events for the evaluation of fuel performance for a BWR. In ATWS instability the BWR will be at low flow for natural circulation and experience power oscillations. During these oscillations the high power fuel bundles may undergo periodic boiling transition and rewet following each power pulse. As long as the PCT remains below the minimum film boiling temperature, rewet will occur and excessive fuel heat up is avoided. However, if the cladding temperature exceeds the minimum film boiling temperature (approximately 600 ^{0}C (1100 ^{0}F)) following a power pulse the fuel may not rewet and substantial fuel heat up can occur.

Data for transient dryout, post dryout heat transfer and transient rewet have been obtained since the mid sixties. The data include simple geometry tests as well as full scale simulated fuel bundles.

Simple geometry data[1,2,3] have typically been obtained in tubular and annular geometries and include steady state as well as transient tests. These tests typically give well defined thermal hydraulic data and are excellent for model qualification. They do, however not provide information on the cross sectional variation of thermal hydraulic conditions in a rod bundle. The maximum peak cladding temperature (PCT) for these tests goes well beyond the minimum film boiling temperature, where rewet is not obtained. These tests therefore provide valuable information on boiling transition, film boiling heat transfer and rewetting.

Similar tests have been obtained in simple rod bundles,[4,5,14] typically 4X4 rod bundles. In these tests both steady state and transient tests have been performed. The steady state test were used to obtain information on film boiling heat transfer, while the transient tests were used to obtain additional information on transient dryout and rewet. The transients were either simple power and flow transients where either the power was temporarily raised or the flow temporarily reduced to obtain a boiling transition, or they were simulation of a reactor turbine trip or recirculation pump trip. These tests also give PCTs beyond the minimum film boiling temperature and provide valuable information on boiling transition, film boiling heat transfer and rewetting.

BWR fuel vendors perform extensive critical power tests for each new fuel product that is developed. Steady state critical power data over a range of parameters covering normal steady state operation as well as the expected range of parameters for operational transients. These data are used to develop a fuel type specific critical power correlation. In addition a few transient tests are usually performed in order to demonstrate the applicability of the correlation under transient conditions.[6,7,8,11,19,27,28,29,30,31] The transient tests are simulated turbine trip and recirculation pump trip transients, and in one instance a reactor instability was simulated. Since the transient tests are intended to demonstrate the applicability of the critical power correlation under transient conditions, the PCT typically does not exceed the saturation temperature by more than 100-200 ^{0}C and thus does not provide data beyond the minimum film boiling temperature.

Numerous loss of coolant accident (LOCA) experiments have provided information on transient dryout, film boiling heat transfer and transient rewet. These tests include data from the BDHT,[15] TLTA,[16] FIST,[17,18] FIX,[9,10,21,22,23] TBL,[24] and ROSA-III[25,26] test facilities, which are all scaled simulations of BWRs. The upper range of PCTs for these tests is approximately 870 ^{0}C (1600 ^{0}F). High temperature data up to 1150 ^{0}C (2100 ^{0}F) have been obtained in GE's core spray heat transfer test facility and from the GOTA test facility and similar facilities at Hitachi and Toshiba.[20]

Finally in-pile test have been performed, where nuclear fuel rods have been subject to boiling transition during power and flow transients. Even though the primary purpose of these tests was to evaluate the thermal and mechanical response of the fuel, these tests also provide valuable data on transient dryout and rewet. The early data in the van Houten report[13] were collected for exposures up to 20 GWd/t and peak cladding temperatures up to 1700 ^{0}C. The later data from the Halden test reactor[13] had exposures up to 40 GWd/t and peak cladding temperatures up to 950 ^{0}C.

The transient dryout and rewet tests are summarized in the table that follows the references.

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Transient Dryout and Rewet Tests.

Geometry	Test Type	PCT	References
Simple Geometry Tests			
Tubular and Annular	Steady State and Transient	850 ^{0}C	1, 2, 3

Simple Rod Bundles			
4X4 Rod Bundles	Steady State Film Boiling Flow and Power Transients Simulated Turbine and Pump	715 ^{0}C	4, 5, 14
Full Scale Rod Bundles			
	Simulated Turbine and Pump Trips for 8X8, 9X9 and 10X10 Rod Bundles		6, 7, 8, 11, 19, 27, 28, 29, 30, 31
LOCA			
Scaled Simulation of a BWR.	BDHT, TLTA, FIST, FIX, TBL, ROSA	870 ^{0}C	9, 10, 15, 16, 17, 18, 21, 22, 23, 24, 25, 26
Core Spray Heat Transfer	CSHT, GOTA. Toshiba, Hitachi	1150 ^{0}C	20
In-Pile Data			
	Flow and Power Transients	1700 ^{0}C	12, 13

Note: Minimum Film Boiling Temperature 600 ^{0}C.

Dryout Effects on High Burnup Fuel (OECD Halden Reactor Project-Norway)

The information regarding this test series was provided by panel-member W. Wiesenack.

Background

The objective of the dry-out test series was to provide information on the consequences for fuel of short-term dry-out incidents in a BWR. The experimental method employed was, on an individual basis, to expose fuel rod with different burnups to single or multiple dry-out events; to follow this by either unloading or continued operation in the reactor; and to finish with post irradiation examination and testing with emphasis on fuel clad properties. The test series was co-sponsored by the Halden Project's joint program and TEPCO (Japan).

Testing program

The test series comprised three loadings of IFA-613. Each rod was contained in a stainless steel channel within the rig so that the coolant conditions for each rod could be controlled individually. In this way separate dry-out scenarios were effected for each rod. Thermocouples attached to the surface of the test rods were used to monitor clad surface temperature and clad elongation was monitored by way of an extensometer. The first and second loading operated for a month after dry-out whilst the rods in the last loading were unloaded directly after the dry-out procedure. In neither case did any fuel failures develop.

The in-pile dry-out experiments with the third (and last) set of fuel rods in IFA-613 were completed in January '98 (HWR-552, HP-1036) and the post irradiation examination

(PIE) on all eight rods in the three test series were finished in September '98 (Kjeller hot cell).

Summary of results

In total, 2 rods with fresh Zr-2 and Zr-4 and 6 rods with clad pre-irradiated to 22-40 MWd/kg (Zr-2, Zr-2 with liner and Zr-4) were individually exposed to reduced or no-flow conditions in a heated light water loop within the Halden reactor. Dry-out occurred over the upper region of each rod, with 6 rods developing peak clad temperatures in the range 950-1200°C occurred in the other two rods.

An overview of the condition of the rods in terms of clad surface condition, rod dimensions and hydriding was achieved using non-destructive PIE techniques such as profilometry and neutron radiography. Clad and fuel microstructure and clad mechanical properties were investigated with destructive PIE techniques including ceramography, metallography, microhardness and ring tensile testing. It was observed that whilst dry-out had not affected the fuel microstructure, significant changes had been induced in the clad. These included high temperature corrosion resulting in moderate growth of the outer surface oxide layer and H_2 pick-up (hydriding formation). Some of the rods also exhibited uniform and localised clad creep-down into pellet-pellet interfaces and in the most severely tested rods that clad had undergone the α to β phase transformation. This material exhibited reduced UTS and brittle fracture. However, significant improvements of ductility were observed in clad that had been exposed to less severe in-pile transients where a small α-phase grain structure was retained and hydrogen pick-up was minimal. None of the rods failed, neither during the dry-out phase or the following steady-state normal operation.

Applications

The data obtained will be used to assess and modify existing rules/regulations in member countries on the continued operation with fuel elements subjected to short-term dry-out transients in boiling water reactors.

APPENDIX F

MEMBERS OF THE HIGH BURNUP FUEL PIRT PANEL

Carl A. Alexander

Carl Alexander is Chief Scientist of Battelle's government sectors operation. He has a B.S. in Mathematics from Ohio University, a M.S. in Physics from the same institution, and a Ph.D. in Ceramic Engineering received in 1961 from The Ohio State University. From 1962 to 1985 he was a member of the engineering and graduate faculty of The Ohio State University, with joint appointments as Adjunct Professor of Nuclear Engineering as well as Ceramics and Materials Engineering. He has also served as Adjunct Professor at the University of Maryland and Southampton University in the U.K. His specialty is nuclear fuels and thermodynamics. He performed some of the first loss-of-coolant simulations in the late 1950s early 1960s. He contributed to Wash-1400 in which he showed the importance of cesium iodide as a transport medium in a LOCA. He performed several studies of fission product release with real fuels at very high temperatures and has evaluated a number of complexes involving urania and Zircalloy at very high temperatures.

Jens G. M. Andersen

Jens G. Munthe Andersen is a principal engineer at Global Nuclear Fuel. He has a M.S. in Nuclear Engineering for the Technical University in Denmark and obtained a Ph.D. in Nuclear Engineering from the same institution in 1974. From 1971 to 1978 he was employed by Risø National Laboratory in Denmark. From 1978 Dr. Andersen has been employed by General Electric Nuclear Energy and since January 2000 by Global Nuclear Fuel (a joint venture of GE, Toshiba and Hitachi). He is currently leader of the Methods and Process Development team at Global Nuclear Fuel. Dr. Andersen has 29 years experience in the nuclear field. He has been primarily engaged in developing computer programs for boiling water reactor transient and safety analysis. He has participated in numerous PIRT panels and the application of the CSAU methodology to BWR.

John A. Blaisdell

John Blaisdell is a Senior Consulting Engineer at Westinghouse Electric Company (CE Nuclear Power, LLC). He received his BS degree in Mechanical Engineering from Clarkson University in 1961 and a Ph.D. in Mechanical and Aerospace Engineering from North Carolina State University in 1969. Dr. Blaisdell has worked in the nuclear industry for that past 29 years. His experience includes work on the PWR FLECHT-SEASET experimental program, including test specification development and review and correlation of results; development of best-estimate small break LOCA analytical methods; and supervising the development of mathematical models of fuel behavior during a LOCA. He was the Manager of Safety Analysis at Northeast Utilities where he managed the development of plant-specific probabilistic safety analyses (PSAs) for four nuclear units and the in-house development of transient and LOCA analysis capability. He was also a project manager at Yankee Atomic Electric Company where he managed the development of a best-estimate containment analysis for the Maine Yankee power plant. This work included facilitating a PIRT panel and managing the development of the methodology to statistically combine the results of the mass and energy calculations with the containment response calculations. Dr. Blaisdell is currently involved in the LOCA and non-LOCA safety analyses for both PWRs and BWRs.

Brent E. Boyack

Brent E. Boyack is the facilitator for the High Burnup Fuel PIRT Panel. He is a registered professional engineer. He obtained his B. S. and M. S. in Mechanical Engineering from Brigham Young University. He obtained his Ph.D. in Mechanical Engineering from Arizona State University in 1969. Dr. Boyack has been on the staff of the Los Alamos National Laboratory for 19 years; he is currently the leader of the software development team, continuing the development, validation, and application of the Transient Reactor Analysis Code (TRAC). Dr. Boyack has over 30 years experience in the nuclear field. He has been extensively engaged in accident analysis efforts, including design basis and severe accident analyses of light water, gas-cooled, and heavy-water reactors; reactor safety code assessments and applications; safety assessments; preparation of safety analysis reports; and independent safety reviews. He chaired the MELCOR and CONTAIN independent peer reviews and was a member of the Code Scaling, Applicability and Uncertainty or CSAU technical program group. He has participated in numerous PIRT panels. He has over 70 journal and conference publications and is an active member of the American Nuclear Society.

Bert M. Dunn

Bert M. Dunn obtained his B. S. in Physics from Washington State University in 1968 and his M. S. in Physics from Lynchburg College in 1973. Mr. Dunn has worked in LOCA and Safety Analysis for the Babcock and Wilcox Company (B&W) and Framatome Technologies (FTI) for 28 years. Mr. Dunn has served as the lead technically for the development of the B&W and FTI LOCA evaluation models for once through and recirculating steam generator plants. He has worked with both deterministic and best estimate LOCA evaluation techniques. He has also been technical lead for method development and application of boron dilution accident methods and pressurized thermal shock evaluation methods. He is currently employed as an Advisory Engineer with responsibility for the development of LOCA and Safety Analysis techniques for evaluation of advanced cladding materials. This includes test specification development, review and correlation of results, and the incorporation of results into requisite analytical methods. Mr. Dunn has been primary author on several company topical reports covering both methods development and accident analysis.

Derek B. Ebeling-Koning

Derek B. Ebeling-Koning is Manager of BWR Fuel and Engineering Analysis at Westinghouse Electric Company. He received his B.S. degree in Nuclear Engineering from Rensselaer Polytechnic Institute in 1977. He received his M.S. and Ph.D.degrees in Nuclear Engineering in 1979 and 1983, from Massachusetts Institute of Technology. He has worked for the last 17 years in BWR and PWR safety analysis, initially for Westinghouse Electric, then ABB Combustion Engineering starting in 1991 (now a subsidy of Westinghouse Electric.) His expertise includes methods and modeling of two-phase flow; BWR LOCA analysis, PWR operational transients and containment analysis; and a lead role in developing and licensing of ABB BWR reload analysis methodology in the U.S. Dr. Ebeling-Koning is a member of the ANS and ASME, and technical reviewer for several industry journals.

Toyoshi Fuketa

Toyoshi Fuketa is a Principal Engineer in the Fuel Safety Research Laboratory at the Japan Atomic Energy Research Institute (JAERI). He obtained his B. S., M. S. and Ph.D. in Mechanical Engineering Science from Tokyo Institute of Technology, Japan, in 1982, 1984 and 1987, respectively. Dr. Fuketa has been involved in the Nuclear Safety Research Reactor (NSRR) project to study behavior of LWR and research reactor fuels under reactivity accident and severe accident conditions and to evaluate the thresholds, modes, and consequences of fuel failure in terms of the fuel enthalpy, fuel burnup, coolant conditions, and fuel design. His research interests include fuel-coolant interactions, fuel failure mechanisms and transient fission gas behavior. He was engaged in small-scale steam explosion experiments at Sandia National Laboratories, Albuquerque, from 1988 to 1990, as a visiting scientist.

Georges Hache

Georges HACHE is a PIRT expert on LOCA fuel behavior from the French Nuclear Safety and Protection Institute (IPSN). He graduated from the French Ecole Polytechnique in 1973 and Ecole des Mines de Paris in 1976 (colleges of university level, admission to which is by strict examination). After ten years in the French nuclear inspectorate, he joined the IPSN Safety Research Division at Cadarache in 1986. He was involved in the development and assessment of safety computer codes, describing fuel and fission products behavior during severe and design basis accidents of light water and fast breeder reactors (SCANAIR, ICARE2, ESCADRE...), including definition and interpretation of safety tests in the CABRI and PHEBUS reactors. After having led the safety software development and assessment team for a period of seven years, he is now senior scientific adviser to the head of the Division. He has been engaged in international cooperative efforts including the OECD / CSNI Rasplav program and a task force on fuel safety criteria.

Lawrence E. Hochreiter

L.E. (Larry) Hochreiter is a professor of Nuclear and Mechanical Engineering at the Pennsylvania State University and does research and teaching in the areas of two-phase flow and heat transfer, reactor thermal-hydraulics, fuel rod design, and nuclear reactor safety. He recieved a BS degree in Mechanical Engineering from the Universtiy of Buffalo and a MS and Ph.D degrees in Nuclear Engineering from Purdue University. While at Pennsylivania State University, Dr. Hochreiter has developed a detailed reflood heat transfer PIRT to guide the design and instrumentation of the NRC Rod Bundle Heat Transfer program, located at Penn State. Before joining the Penn State University in 1997, Dr. Hochreiter was a Consulting Engineer at the Westinghouse Electric Corporation for nearly 26 years and was responsible for the development, testing validation, and licensing of Westinghouse safety analysis methods. He developed the large-break Loss Of Coolant Accident (LOCA) PIRT for the Westinghouse Best-Estimate Methodology. He also participated in and helped develop the Westinghouse small-break LOCA PIRT. Dr. Hochreiter also developed several PIRTs for the Westinghouse advanced AP600 design for the accident analysis methods and presented these PIRTs to the NRC and the ACRS.

S. E. "Gene" Jensen

S. E. "Gene" Jensen is an experienced engineer with 38 years of involvement in nuclear safety applications and development. Mr. Jensen obtained his BS degree in 1961 from Montana State and his MS degree from the University of Idaho both in Chemical Engineering. He is a registered professional engineer. He spent the first 14 years of his career at the Idaho National Engineering Laboratory working in various phases of the nuclear safety test engineering program. He became involved with the early regulatory support activities including the development of the Water Reactor Evaluation Model (WREM) to perform LOCA analyses according to the NRC ECCS Rule which came out in 1975. In 1975, Mr. Jensen joined Exxon Nuclear Company (since purchased by Siemens), where he was instrumental in developing LOCA ECCS Evaluation Models for both PWRs and BWRs and obtaining NRC approval of these models. Mr. Jensen has spent 24 years with what is now Siemens Power Corporation all of which were involved with safety analysis applications and development including both transient and LOCA analysis. His most recent involvement has been as the technical lead in developing a PWR Realistic LOCA methodology for Large Break LOCA. Mr. Jensen is a member of both ANS and AIChE.

Siegfried Langenbuch

Siegfried Langenbuch is head of the reactor dynamics division of GRS. He obtained his Diploma in Physics from the University of Munich in 1969. The objective of his Dr. degree work was the development of an efficient spatial- and time-dependent 3D-neutronics model for studying reactivity initiated accidents. His research interests were code development for neutron dynamics and thermo-fluid dynamics of the reactor core, including the coupling of 3D-neutronics models with plant system codes. In addition, he has experience in safety review of nuclear design, thermal design, and accident analysis of BWRs and PWRs as well as of VVERs and RBMKs of Russian design. He is a member of national and international working groups for the requirements of nuclear design. He has numerous publications in the field of reactor core dynamics.

Frederick J. Moody

Frederick J. Moody is a Consulting Engineer in Thermal-Hydraulics, who has participated in numerous NRC - sponsored peer review groups and Technical Program Groups, involving the analysis of postulated nuclear reactor accidents. He received his Ph.D. in Mechanical Engineering from Stanford University in 1971. He completed 41 years of reactor and containment safety analyses at the General Electric Nuclear Energy Division, where he developed various industry-standard analytical models for studies involving pipe and component rupture blowdown of high pressure steam and water mixtures, containment pressure and jet impingement loads, waterhammer forces associated with pipe flow accelerations, dynamic and thermal response of nuclear reactor core components during accident conditions, and fluid-structure interaction of submerged structures. He has taught numerous engineering courses as an adjunct professor for 28 years at San Jose State University, as an in-plant instructor at General Electric, and more recently as an instructor for professional development courses sponsored by the American Society of Mechanical Engineers. He has authored numerous journal papers, written an engineering textbook, *Introduction to Unsteady Thermo-Fluid Mechanics* (Wiley Interscience, 1990), and co-authored *The Thermal-Hydraulics of a Boiling Water Nuclear Reactor*, 2nd Ed., ANS Press, 1993.

Arthur T. Motta

Arthur T. Motta has worked in the area of radiation damage to materials with specific emphasis in Zr alloys for the last fifteen years. He received a B.Sc. in Mechanical Engineering and an M.Sc. in Nuclear Engineering from the Federal University of Rio de Janeiro, Brazil, and a Ph.D. in Nuclear Engineering from the University of California, Berkeley. He worked as a research associate for the CEA at the Centre for Nuclear Studies in Grenoble, France for two years and as a post-doctoral fellow for AECL at Chalk River Laboratories, Canada, before joining Penn State in 1992. The research programs he developed at Penn State include mechanical behavior of Zr alloys, advanced techniques for characterization of Zr alloys, and its oxides, defects in intermetallic compounds and phase transformation under irradiation. He has expertise in transmission electron microscopy, charged particle irradiation, mechanical testing, positron annihilation spectroscopy and theoretical expertise on phase transformations under irradiation and microstructural evolution under irradiation. He has recently authored review articles on amorphization under irradiation and on zirconium alloys in the nuclear industry. He was recently guest editor for a special issue of the Journal of Nuclear Materials, and was a member of a DOE panel to evaluate research needs on radiation effects on ceramics for radioactive waste disposal.

Mitchell E. Nissley

Mitchell E. Nissley obtained his B. S. and M. Eng. degrees in Nuclear Engineering from Rensselaer Polytechnic Institute. Mr. Nissley has been on the staff of the Westinghouse Electric Company for 18 years; he is currently the leader of the team responsible for the development, licensing and application of the various realistic large break LOCA analysis codes and methodologies employed by Westinghouse. His contributions to the nuclear industry include the development and licensing of critical heat flux correlations for advanced PWR and VVER fuel designs, and the development and licensing of realistic large break LOCA evaluation models for Westinghouse PWR designs (cold leg injection, upper plenum injection and AP600). He has numerous journal and conference publications.

Katsuhiro Ohkawa

Katsuhiro Ohkawa is an advanced technical engineer at Westinghouse Electric Company. He received his BS in Physics from Sophia University in Tokyo, MS (1978) and PhD (1983) in Nuclear Science and Engineering from Rensselaer Polytechnic Institute. His experience at Westinghouse includes the development of Liquid Metal Advanced Nuclear Plants, BWR and PWR safety methods. Since 1990, he has been involved in the development of CSAU based Best Estimate Large Break. Currently he is involved in the development of Best Estimate Small Break LOCA Methodology.

Kenneth L. Peddicord

Kenneth L. Peddicord is Associate Vice Chancellor and Professor of Nuclear Engineering at Texas A&M University. He received his B.S. degree in Mechanical Engineering from the University of Notre Dame in 1965. He obtained his M.S. degree in 1967 and his Ph.D. degree in 1972, both in Nuclear Engineering from the University of Illinois at Urbana-Champaign. From 1972 to 1975, Dr. Peddicord was a Research Nuclear Engineer at the Swiss Federal Institute for Reactor Research (now the Paul Scherrer Institute) where he worked in the plutonium fuels program. From 1975 to 1981, Dr. Peddicord was Assistant and Associate Professor in the Department of Nuclear Engineering at Oregon State University. From 1981 to 1982, he was a Visiting Scientist at the EURATOM Joint Research Centre in Ispra, Italy where he was involved in the Super Sara Severe Fuel Failure Programme. In 1983, Dr. Peddicord joined Texas A&M University as Professor of Nuclear Engineering. He has served as Head of the Department of Nuclear Engineering (1985-88), Associate Dean for Research (1988-91), Interim Dean of Engineering (1991-93), and Director of the Texas Engineering Experiment Station (1991-93). Since 1994, he has been Associate Vice Chancellor of the Texas A&M University System. Dr. Peddicord serves as the representative of the A&M System to the Governing Board of the Amarillo National Resource Center for Plutonium. Dr. Peddicord's research interests are in the performance and modeling of advanced nuclear fuels. Since 1995, he has been a participant in joint DOE-Minatom activities on excess plutonium disposition and nuclear materials safety. Dr. Peddicord has 120 publications in technical journals and conferences. He is a registered professional engineer in the state of Texas and has been a member of the American Nuclear Society since 1975.

Gerald Potts

Mr. Potts of Global Nuclear Fuel received a Bachelor of Science degree in Mechanical Engineering from the University of California, and a Master of Science degree in Mechanical Engineering from Santa Clara University. Mr. Potts has accumulated 28 years experience in the commercial nuclear power industry within the General Electric Nuclear Energy division. Mr. Potts' responsibilities and experience include fuel rod thermal-mechanical design, fuel rod thermal-mechanical performance and licensing basis analytical model development, and fuel integrity assessment under normal steady-state operation, anticipated operational transient, and accident conditions.

Joe Rashid

Joe Rashid is a Fellow of the ASME and a registered Nuclear Engineer. His general field of expertise is computational thermo-mechanics, structural mechanics and material constitutive modeling. He acquired his graduate and undergraduate education in mechanics at the University of California Berkeley, receiving the PhD degree in 1965. Having received his education at the birth place of the Finite Element Method in the early sixties, Dr. Rashid was among the pioneering contributors to its development, in particular three-dimensional computations. Dr. Rashid's three and a half decades career in the nuclear industry began with the gas-cooled reactor technology at General Atomics in San Diego, followed by an eight-year career in BWR technology at General Electric in San Jose, and finally at ANATECH Corp. which he founded in 1978. At General Atomics, his work in the mechanics of concrete reactor vessels and nuclear fuel particles led to the development of the smeared-crack model, which was adopted in finite element codes as the basic model for the cracking analysis of brittle materials. At GE, he was responsible for the development of the industry's first two-dimensional fuel rod behavior code for the analysis of the then-emerging pellet-clad interaction (PCI) problem. At ANATECH, Dr. Rashid undertook the development of the transient fuel analysis code FREY for the Electric Power Research Institute (EPRI). In the aftermath of the Three Mile Island accident, EPRI's collaboration with Sandia in reactor containment research, with Dr. Rashid as the principal investigator for EPRI, led to the institutionalization of the leak-before-break concept for reactor containment structures, thereby profoundly affecting risk assessment of loss of coolant accidents. He participated in severe accident work with Sandia and EPRI, which included the development of constitutive models and analysis methods for the creep rupture of pressure vessel lower head under loss of coolant accident. He participated in the expert review process for NUREG-1150, and was nominated by NRC to chair an international expert panel for OECD'sVessel Investigation Project. Dr. Rashid's publications in the various fields of activity in which he had primary contributions exceed 100, which include journal articles, reports and white papers.

Richard J. Rohrer

Richard J. Rohrer serves as a member of the High Burn-up Fuel Phenomena Identification and Ranking Table (PIRT) Panel. He is a registered professional engineer in the state of Minnesota. He obtained a B.S. in Nuclear Engineering from the University of Illinois, and an M.S. in Nuclear Engineering from the University of Wisconsin in 1983. He also holds an M.S. in Management from Cardinal Stritch College, and a Senior Reactor Operator Certification for the Monticello Nuclear Generating Plant. Mr. Rohrer has over 16 years experience supporting operations of nuclear power reactors, including licensing, reactor engineering, probabilistic safety assessment, core design, accident analysis, and transient analysis. He currently manages projects for the Monticello Nuclear Generating Plant in the Nuclear Analysis and Design group with Nuclear Management Company. Mr. Rohrer is a member of the American Nuclear Society and has published five technical papers on probabilistic safety assessment and Boiling Water Reactor stability. In addition, he is an active participant in the Electric Power Research Institute's Robust Fuel Program.

James S. Tulenko

James S. Tulenko is Chairman of the Nuclear and Radiological Engineering Department and a Professor of Nuclear Engineering at the University of Florida. He received his B.A. with honors in Engineering Physics from Harvard College and his M.A. in Engineering Physics from Harvard University in 1960. After military service in the Corps of Engineering, he obtained a M.S. in Nuclear Engineering from the Massachusetts Institute of Technology in 1963. In 1980 he obtained a M.E.A. from George Washington University. Professor Tulenko's professional activities have included all aspects of the nuclear fuel cycle. He has over 35 years of experience in fuel design, fuel operation and fuel performance. Professor Tulenko was Manager of Nuclear Development at United Nuclear Corporation where he patented the water hole thermalization concept now utilized in all boiling water reactors. He also was project engineer for one of the first Plutonium reloads in a commercial reactor. He served as Manager of Physics for Nuclear Materials and Equipment (NUMEC) Corporation where he headed up nuclear physics activities. He later served as Manager of Physics and Manager of Nuclear Fuel Engineering for the Nuclear Power Division of Babcock and Wilcox. In 1979 he was made a Fellow of the American Nuclear Society (ANS) for his contributions to the fuel cycle. In 1980 he received the Silver Anniversary Exceptional Service Award of the ANS for his outstanding contributions to the Nuclear Fuel Cycle in the first 25 year of the ANS. In 1997 he received the Mishima Award of the ANS given for outstanding contributions to Nuclear Material Research. He also was awarded the Glenn Murphy Award of the American Society of Engineering Education given to the Outstanding Nuclear Engineering Educator. He is a Board Member of the National Nuclear Accrediting Board of the Institute of Nuclear Power Operations and a Board Member of the American Nuclear Society. He is also a Commissioner of the Engineering Accreditation Commission. He has over 100 journal and conference publications and has consulted for a variety of government agencies and commercial companies.

Keijo Valtonen

Keijo Valtonen is a Chief Inspector with the Radiation and Nuclear Safety Authority of Finland. He obtained his degree from the University of Helsinki where he majored in reactor physics and thermal hydraulics. His primary duties since 1975 have been fuel, nuclear and thermal-hydraulic design of reactor cores; transient and accident analysis for Loviisa (VVER-440 type PWR) and Olkiluoto (ABB-Atom type BWR); and operator qualification, including oral licensing examinations and review of operator instructions. He has reviewed plant feasibility studies, including those for the VVER-1000, ABB-Atom BWR 90, Siemens PWR, and SECURE and PIUS. He has reviewed numerous feasibility studies for new fuel designs, including VVER Zr 1% Nb, BNFL-VVEF fuel, ABB 8x8, SVEA 64, SVEA 100, Siemens 9x9, GE12 and Siemens ATRIUM 10. He has participated in safety reviews for the RBMK. He has engaged in research work on the transient behavior of BWR and PWR reactor cores, BWR stability analysis, validation of TRACB and RAMONA computer codes, PWR boron dilution, and several fuel transient behavior studies for VVER and BWR reactors. He has been engaged in international cooperative efforts including IAEA and OECD development of safety criteria for future nuclear reactors, regulatory approaches to severe accident issues for the OECD/CNRA, a state-of-the-art report on BWR stability, the European Union's safety RBMK safety review, the OECD/CSNI task force of fuel safety criteria.

Nicolas Waeckel

Nicolas Waeckel was the Technical Leader and Manager of the Nuclear Fuel Design and Survey Group at Electricite de France (EDF) Septen. He is now working at EPRI as a project manager of the Working Group 2 (response in transient) within the Robust Fuel Program. At EDF he developed and managed $18 M per year fuel R&D programs including $6 M per year fuel R&D programs about RIA and LOCA issues. He developped and managed activities in areas of Nuclear Fuel Rod and Nuclear Fuel Assembly design, design methodologies and fuel rod performance code developpement (normal operation conditions and accidental conditions). He interacted with the Utility and the French Safety Authorities on many key issues (RIA, LOCA, Fuel Assembly distortion, Burn-up extension, etc...). From 1984 to 1990, he was in charge of the FBR and the LWR Structural Mechanics Design Group thereafter. He developped several design methodologies (Buckling of thin shells, creep-fatigue and progressive deformations) and participated to the writing of the RCCMR (design rules for the FBRs). He managed 15 PH.D. Students and 20 contracts with Universities, CEA and Novatome. He has authored papers and reports in areas of mechanical design of thin structures (buckling, creep-fatigue, ratchetting and fracture mechanics) and nuclear fuel design and performance (PCMI, High burn-up properties, RIA and LOCA). The topic of his Sciences Doctorate Thesis was Impact of initial geometrical defect on buckling of FBR related thin strucures. The topic of his Ph. D. thesis was the Dynamic behavior of short cylindrical shells.

Wolfgang Wiesenack

Wolfgang Wiesenack is the acting general manager of the OECD Halden Reactor Project. He obtained an MS in nuclear engineering from the University of Hanover, Germany, in 1976 and a PhD in nuclear engineering and LWR fuel behavior modeling from the same university in 1983. Dr. Wiesenack had a research assistant position at the University of Hanover, working on LOCA analysis (RELAP 4) and modeling of LWR fuel behavior in normal operating conditions. He joined the OECD Halden Reactor Project in 1984. As senior reactor physicist he was responsible for the core physics calculations of the Halden reactor, including nuclear design studies of experimental rigs, core loadings and updating of the reactor's safety report. He was also responsible for the data acquisition of the reactor and implemented a completely renewed system. As the head of the Data Acquisition & Evaluation division, he was in direct contact with many aspects of fuels and materials behaviour under steady state and ramping and transient conditions. He was actively engaged in the execution of the IAEA code comparison exercise FUMEX to which the Halden Project provided the data. He was also a member of the FRAPCON peer review team. He is a member of the German nuclear society.

APPENDIX G

DESCRIPTION OF PWR FUEL AND CLADDING STATE AT HIGH BURNUP

The extended operational exposure that accompanies high burnup causes changes to the fuel and cladding that may affect the fuel rod's ability to withstand the accident without losing its integrity (Fig. G-1). These changes, which occur gradually over the life of the fuel rod, can be considered as initial conditions for the accident.

There are many changes that occur to the fuel and cladding as a result of prolonged exposure to the irradiation field present in a reactor core, and to the corroding environment and high temperature. The combination of high temperature, radiation damage, transmutation, mechanical stresses and chemical reactions causes the microstructure of cladding and fuel to evolve considerably during reactor exposure. These changes in microstructure, microchemistry, and macroscopic characteristics of pellet and cladding are responsible for the changes in material behavior observed at high burnup. These changes are very complex and difficult to predict in mechanistic fashion. Of the many changes to the fuel and cladding, it is important to discern which are of greatest importance to determining fuel rod behavior during a rod ejection accident. We list some of the more important material degradation phenomena below, recognizing that the list may not be inclusive. The changes to the fuel and cladding are important to both pressurized water reactor (PWR) and boiling water reactor (BWR) fuel types. However, the discussions below will primarily be for PWR fuel because it leads the BWR fuel in terms of both fuel burnup and waterside corrosion.

G.1. Cladding Changes

The main degradation mechanisms to Zircaloy-4 cladding such as are present in TMI include uniform waterside corrosion, hydriding, and radiation damage.

Uniform waterside corrosion occurs throughout the reactor exposure. The corrosion rates depend on many factors including alloy chemistry and thermomechanical treatment, coolant chemistry, radiation-induced changes to cladding microchemistry, and irradiation temperature. For cladding with burnups in excess of 50 GWd/t , the oxide thickness can exceed 100 μm depending on fuel duty, i.e., power and temperature versus time and burnup. The burnup level at which any given oxide thickness is reached for a given alloy is dependent on the fuel duty. The more modern alloys such as ZIRLO and M5, can have lower corrosion rates than standard Zr-4 and low-Sn Zr-4 at similar burnup. All of the zirconium alloys examined to date show a change in corrosion rate when the oxide exceeds a certain thickness (20 to 30 μm in thickness), which indicates a change in corrosion regime, termed **breakaway corrosion.** Therefore, it is likely that even the new modern alloys such as ZIRLO will eventually experience breakaway corrosion. The question with the new modern alloys is the burnup level at which breakaway corrosion will be observed.

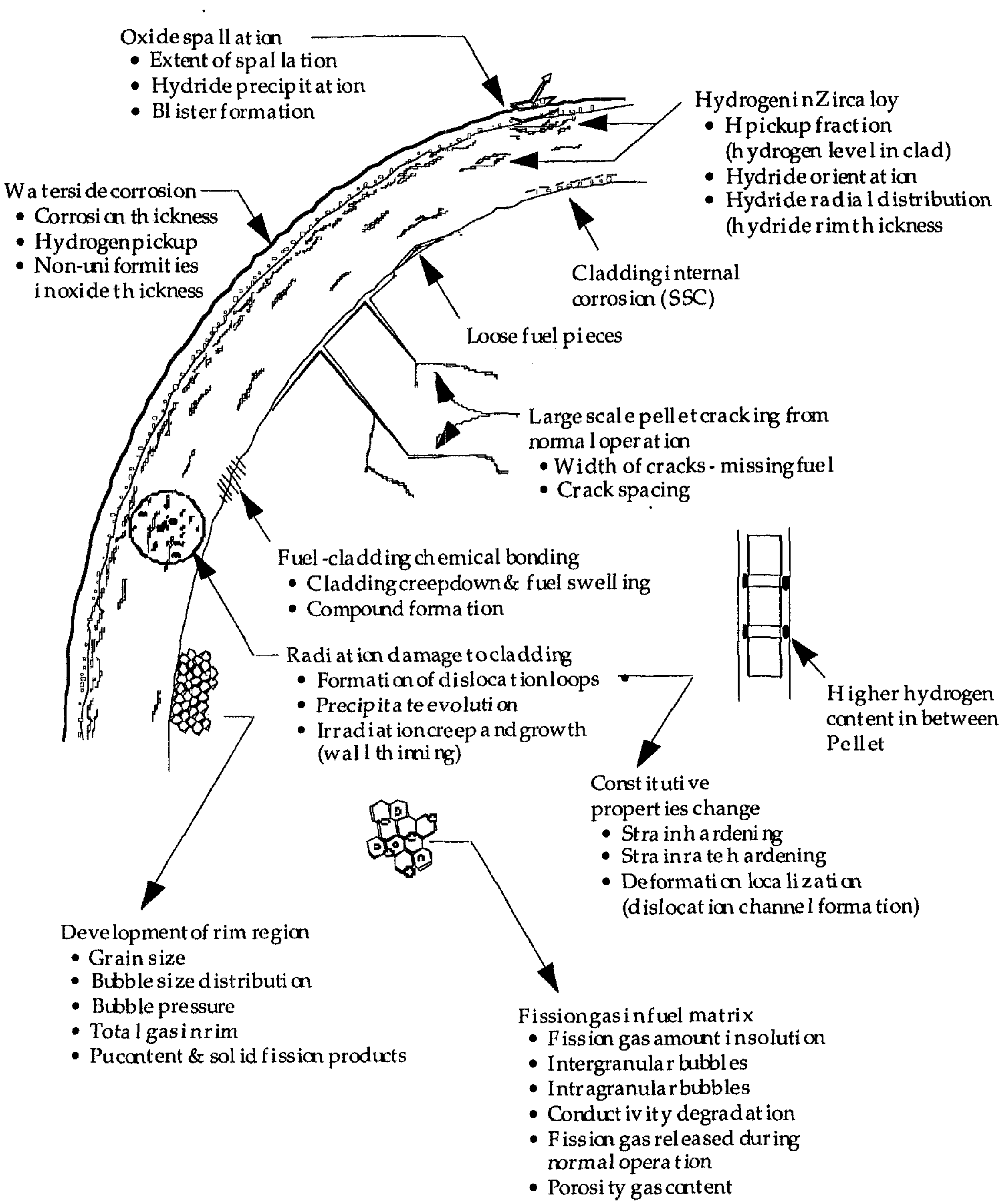

Fig. G-1. Fuel state at high burnup

For example, fuel that experiences a high fuel duty will experience breakaway corrosion at a lower burnup level than fuel with a lower fuel duty. One of the concerns with large oxide thicknesses is the higher probability of **oxide delamination,** whereby portions of the oxide layer are detached from the adherent oxide creating an oxide region with worse heat conduction characteristics. Ultimately the detached oxide can break off (**oxide spalling**) creating a thinner oxide. The associated temperature gradients created by spalling have been shown to influence hydride blister formation in the spalled region[G-1]. The hydride blister is brittle, and its presence has been shown to affect overall cladding ductility.

The main concerns associated with the uniform corrosion process are: (a) potential for oxide spalling resulting in hydride blisters, which affect the overall cladding ductility, (b) loss of thermal conductivity, (c) non-uniform wall thinning (non-uniform oxide), and (d) overall wall thinning.

Hydriding occurs as hydrogen is absorbed into the cladding as a result of the cladding uniform corrosion (roughly 15 to 20% of the hydrogen generated by the corrosion reaction is absorbed into the alloy). This hydrogen precipitates as hydrides throughout the cladding thickness at corrosion thicknesses greater than 50 microns. When the overall hydrogen level is high enough (>1000 ppm), the cladding is brittle when tested at reactor temperature. It is possible that lower levels of hydrogen (600-800 ppm) can affect cladding ductility, especially at lower temperature.

However, lower levels of hydrogen, can also degrade the overall cladding ductility depending on the hydride distribution. The mobility of hydrogen is high, and its solubility in Zircaloy is very low, so hydrogen will tend to precipitate out in any cold spot formed in the material. For example, there is a much greater hydride concentration near the surface of the cladding creating a **hydride rim** with local hydrogen levels higher than 1000 ppm. In addition to being radially localized, the axial distribution of hydrogen is also non-homogeneous, with greater concentration in the region in-between the fuel pellets due to the slightly lower heat fluxes and lower temperatures at pellet interfaces.

The main concerns associated with hydriding are: (a) lower ductility and/or embrittlement resulting from an overall change in constitutive properties, and (b) creation of weak spots in cladding resulting from the formation of a hydride rim, and/or hydride blisters.

Radiation damage. When irradiated to 30 GWd/t (corresponding to a fast fluence of $\sim 10^{22}$ n/cm^2, E>1 MeV) the cladding suffers an amount of damage calculated at about 20 dpa (displacements per atom)[G-2]. The dpa level is roughly proportional to the fluence or burnup, so that 60GWd/t corresponds to about 40 dpa and 75 GWd/t to 50 dpa. This very high level of displacements is translated mostly into radiation-induced dislocation loops, both <a> and <c> type that form from the agglomeration of point defects. Although the overall <a> dislocation density saturates after about one month of reactor irradiation at a level comparable to that found in CWSR cladding, the <c> type dislocations evolve over a more extended period of time. In addition there are microchemical changes in the alloy related to irradiation induced intermetallic precipitate amorphization and dissolution, which can **change corrosion resistance** and hydrogen pickup.

The **constitutive response** of the cladding is also affected by the radiation damage, in particular the dislocation loop microstructure formed under irradiation. The yield stress increases, and the uniform strain decreases, i.e. the material undergoes **hardening** and ductility decrease. The increase in dislocation loop density decreases the strain hardening coefficient of the material. At the microscopic level, these loops can also influence deformation localization at the microscopic level (dislocation channeling); the effects of these microscopic processes on macroscopic deformation and failure are not clear at the moment. There is also **cladding creepdown**, which can cause the gap to be closed, creating the conditions for fuel-clad chemical bonding to develop.

The main concerns relating to radiation damage are (a) radiation hardening and possible embrittlement, (b) change of corrosion resistance through microchemical changes, (c) mechanical property changes and (d) deformation localization (e.g dislocation channeling, possibly leading to easier axial crack propagation).

G.2. Fuel Changes

During normal operation fission gas is formed inside the UO_2 fuel, and distributes itself largely into five inventories: *(i)* gas dissolved in the UO_2 matrix, *(ii)* gas in intragranular (matrix) bubbles, *(iii)* gas in intergranular (on grain boundaries) bubbles *(iv)* gas released to the rod void volume and *(v)* gas in fuel porosity. The amount of gas dissolved in the UO_2 matrix is small, as the solubility of fission gases in UO_2 is low. Contributions *(ii)* and *(iii)* result in fuel swelling with consequent pellet-cladding mechanical interaction (PCMI) and contribution *(iv)* is the result of fission gas release (FGR), which increases the internal rod pressure and results in hoop stress on the cladding. The exact partitioning of these gases among the three inventories are dependent on the power history, temperature, fuel microstructure, etc.

Rim Formation. Because of U-238 resonance neutron capture at the UO_2 pellet surface, the amount of Pu formed in the fuel is greater at the edge of the pellet than in the center. This causes the fission rate at the pellet surface to slowly increase with burnup while the fission rate in the bulk of the pellet decreases. The ratio of fission at the edge of the pellet to the center may be as high as 3 at high burnups. Such a region is called the **rim region** and its thickness is approximately 100 to 300 microns. The rim region is formed when the local burnup at the rim exceeds approximately 60 GWd/t (40-45 GWd/t radial averaged). The **rim region** has a characteristic microstructure that consists of sub-micron size grains with bubbles under high gas pressures and has high porosity (20-30%). Some of these bubbles may be in non-equilibrium with the matrix because there are large strain fields around the smaller bubbles and there is further evidence that they exist within the interior of the pellet as well as on the rim if the irradiation temperatures are low.

The main concerns with the formation of the rim region concern its effects on (a) the amount of fission gas loading and (b) the lubrication (by shearing during deformation, the rim could reduce the friction coefficient between cladding and fuel).

Fuel restructuring and large cracking. These phenomena occur at low burnups when a significant fuel-cladding gap exists. The fuel-cladding gap is either very small or non-existent (as evidenced by chemical bonding) in high burnup fuel even when the fuel is at hot zero power (reactor coolant is still hot). Therefore, these phenomena are not likely to occur in high burnup fuel.

Micro-cracking. The mechanical stresses and thermal stresses present in the fuel during the RIA transient can cause **micro-cracking** to occur at the grain boundaries weakened by gas bubbles. The micro-cracking and its extent can affect both fission gas swelling and deformation.

Pellet-cladding Interface. As burnup increases, a metallurgical or chemical bond starts to form between the cladding and the fuel, so that **fuel-cladding bonding** occurs. Clearly the development of this bond depends on the establishment of clad-fuel contact resulting from creepdown and fuel swelling. At intermediate stages, the friction coefficient will increase but without perfect bonding. It is important to determine the friction coefficient so that we can determine the stress state and failure mode of the cladding during pellet-cladding PCMI.

G.3. References

G-1. M. Garde, G. P. Smith, and R. C. Pirek, "Effects of Hydride Precipitate Localization and Neutron Fluence on the Ductility of Irradiated Zircaloy-4," in *11th International Symposium on Zr in the Nuclear Industry,* vol. STP 1295. Garmisch-Partenkirchen: ASTM, 1996, pp. 407.

G-2. "Standard Practice for Neutron Radiation Damage Simulation by Charged-Particle Irradiation," American Society for Testing and Materials Standard Practice E521-96 (1996).

APPENDIX H

DESCRIPTION OF BWRFUEL AND CLADDING STATE AT HIGH BURNUP

During irradiation, the fuel and cladding experience changes in geometry, material macrostructure and microstructure, mechanical properties, and other physical and performance characteristics. It is considered that some of these changes could possibly affect the fuel rod's ability to maintain its integrity when subjected to an accident. Figure H-1 presents a qualitative characterization of some of these fuel and cladding changes. These changes, which occur generally gradually over the life of the fuel rod, can represent initial conditions for the accident.

Of the many changes experienced by the fuel and cladding, it is important to discern which of these are of greatest importance in determining fuel rod behavior during the power oscillations. Some of the more important phenomena are presented and discussed below, recognizing that the list may not be inclusive. The changes to the fuel and cladding indicated in Figure H-1 are possible, and have been observed, in both pressurized water reactor (PWR) and boiling water reactor (BWR) fuel types, although to varying extents. Recognizing that the power oscillations are a BWR event, the following discussion will attempt to clarify the applicability of the various phenomena as currently recognized in modern commercial BWR fuel.

H.1. Cladding Changes

The cladding material applied in BWRs is Zircaloy-2, most predominately in the annealed, fully recrystallized condition with a zirconium-based inner liner, although cold-worked stress relieved material and non-liner applications also exist. The zirconium liner can contain varying amounts of alloy additions, intended for post-defect corrosion resistance. The primary change mechanisms identified for the cladding are waterside corrosion, hydriding, and radiation damage.

Cladding corrosion occurs through direct exposure of the cladding outer surface to a high temperature, highly oxidizing environment enhanced by the radiation field. The effects of cladding corrosion are wall thinning, increased heat transfer resistance, and cladding hydrogen absorption. In general, the BWR suppliers have progressively refined the cladding material processing to minimize the occurrence of nodular corrosion, thereby resulting in a generally uniform corrosion morphology. Where cladding corrosion distributions are typically peaked at the higher elevations in PWRs, the corrosion distributions are generally flatter along the fuel rod length in a BWR, with possible peaking at the lower elevations. Circumferential variations in cladding oxide layer thickness are observed in BWRs, but are generally minor in magnitude. Where cladding corrosion thicknesses of up to or greater than 100 _m has been observed in PWRs, BWR cladding corrosion is significantly less, typically less than 50 _m at exposures up to ~62 GWd/MTU peak rod average exposure, as observed to date.

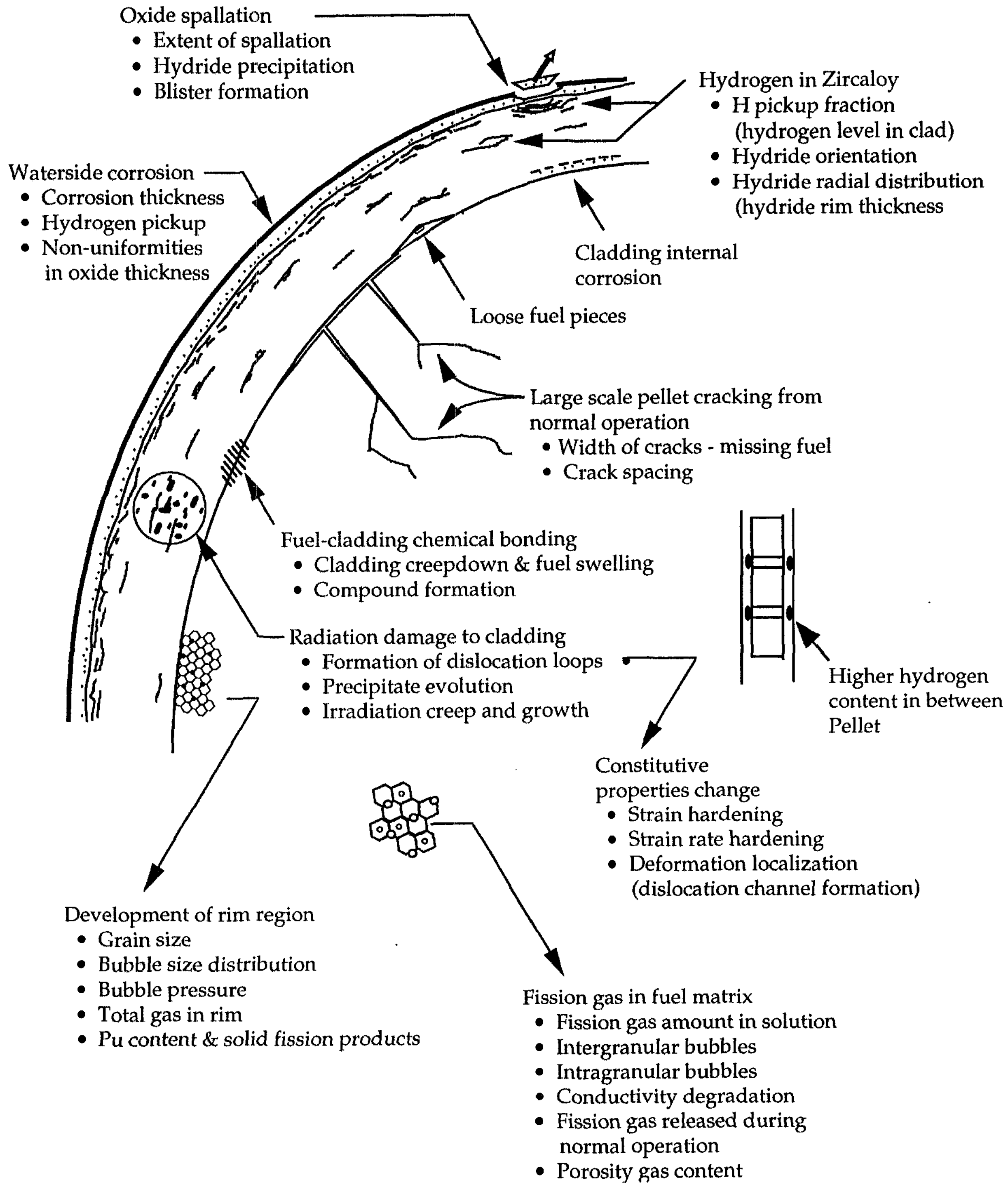

Fig. H-1. Fuel and Cladding State

An important consideration is oxide layer cracking, delamination, and spalling. Oxide layer cracking and delamination can lead to an acceleration in the oxide layer growth rate. Spalled oxide regions result in a cooler cladding metal temperature during operation than exists under the adjacent unspalled oxide regions. The presence of such "cold spots" can promote redistribution of any hydrogen absorbed from the cladding outer surface corrosion process, thereby leading to hydride localizations and even bulk hydride formation (observable as bulges or blisters) in the outer region of the cladding. Such bulk hydride formation regions are highly embrittled and are often accompanied with partial cladding cracks even in the absence of applied loading by the fuel pellets (caused simply by the volume expansion associated with the conversion of zirconium to zirconium hydride). Where significant accelerated corrosion and oxide layer spalling has been observed in PWRs, similar conditions are typically not observed in BWRs with modern cladding materials.

Corrosion localizations have been observed at fuel assembly spacer locations, adjacent to Inconel components (typically referred to as "shadow corrosion"). Although accelerated localized corrosion, leading to fuel rod failure, has occurred at one BWR with an earlier cladding material type, in general, the available characterizations indicate that this localization develops relatively quickly, but then remains relatively stable, at least to exposure levels characterized to date (~62 GWd/MTU peak rod average exposure).

BWRs operate with several water chemistry options: Hydrogen Water Chemistry, Zinc Injection, and Nobel Metal Chemical Addition. To date, no unacceptable changes in the cladding corrosion performance have been observed under these water chemistry options.

In summary, in BWRs with modern cladding, the primary effects of interest from the corrosion process are (1) wall thinning, (2) increased heat transfer resistance, and (3) the effects of corresponding hydrogen pickup.

Hydriding occurs as hydrogen, liberated by the cladding outer surface corrosion process, is absorbed into the cladding. Typically, less than 20% of the hydrogen generated by the corrosion reaction is absorbed by the cladding. This absorbed hydrogen generally precipitates as circumferentially oriented zirconium hydride stringers when the amount of absorbed hydrogen exceeds the solubility level. Available testing has demonstrated no adverse influence of hydrogen on elevated temperature irradiated Zircaloy ductility (total elongation) for hydrogen contents up to at least 850 ppm[G-1]. At higher hydrogen levels, something in excess of 1000 ppm, the cladding ductility can be reduced at operating temperatures. Most typically, BWR cladding hydrogen content is <200 ppm, as characterized at ~50 GWd/MTU rod average exposure for modern BWR cladding materials. Although higher levels (less than 600 ppm) have been observed in older cladding types at elevated exposures (up to ~65 GWd/MTU rod average exposure), even this level is below that required to significantly affect the cladding mechanical properties.

At high hydrogen levels (in excess of 1000 ppm) a dense hydride rim can form near the cladding outer surface, primarily as observed in PWR fuel applications. Hydride localizations have also been observed at "cold spots" occurring at pellet-pellet interfaces (adjacent to pellet chamfers), and more significantly, at spalled oxide locations as discussed previously. With the generally lower hydrogen concentration observed in BWR fuel, dense hydride rims or extreme localizations at pellet-pellet interfaces have not typically been observed, although the general tendency of hydride accumulations toward the cladding outer surface or near pellet-pellet interfaces has been observed.

Another consideration, although not typically observed in either PWR or BWR applications is the development of radially oriented hydrides, which, in significant concentration, could affect the cladding ductility.

In summary, in BWRs with modern cladding, the primary considerations with cladding hydrogen content are (1) the impact, if any, on the cladding mechanical properties, and (2) the effect of hydride localizations to form weak, damage-susceptible regions. In general, these considerations have not been found to be significant for the hydrogen contents observed in modern BWR cladding to date.

Radiation Damage to the cladding material occurs as a direct consequence of exposure to fast neutrons. This radiation damage is manifested as radiation-induced dislocation loops, both <a> and <c> type that form from the agglomeration of point defects. Although the overall <a> dislocation density saturates very early in life, the <c> type dislocations evolve over a more extended period of time. The effect of this damage is a strengthening of the material, with a corresponding reduction in ductility, and increased irradiation-induced stress-free growth (occurs in the absence of an applied stress). Additionally, microchemical changes occur as the irradiation induces intermetallic precipitate amorphization and dissolution, which can alter the mechanical properties, corrosion resistance and possibly also the hydrogen pickup of the cladding material.

In addition to irradiation-induced growth of the cladding material, irradiation also induces cladding creep in response to the applied fuel rod internal-external pressure difference and pellet expansion loadings.

In summary, the primary considerations relative to cladding radiation damage are (1) radiation hardening and the corresponding mechanical properties impact, and (2) deformation caused by irradiation-induced growth and creep.

H.2. Fuel Changes

Fission Products. During normal operation, solid and gaseous fission products are generated within the UO_2 fuel pellet. Whereas the solid fission products generally remain at the birthsite, the gaseous fission products are more mobile and distribute largely into five separate inventories: *(i)* gas dissolved in the UO_2 matrix, *(ii)* gas in intragranular (matrix) bubbles, *(iii)* gas in intergranular (on grain boundaries) bubbles *(iv)* gas released to the fuel rod void volume and (*v*) gas in fuel porosity. The amount of gas dissolved in the UO_2 matrix is limited by the solubility in UO_2. Solid fission products result in a progressive swelling of the fuel material with irradiation exposure. Gaseous fission product inventories *(iii),* and to a lesser extent *(ii) and (v),* under high temperature low restraint conditions, can also result in fuel swelling with consequent pellet-cladding contact. Inventory *(iv)* is referred to as fission gas release (FGR) and produces an increase in the fuel rod internal pressure and corresponding cladding loading. The exact partitioning of the fission gases among the identified inventories is dependent primarily on the fuel pellet microstructure and thermal operating history.

Rim Formation. As a result of U-238 resonance neutron capture at the UO_2 pellet periphery, the amount of Pu formed in the fuel pellet is greater at the pellet periphery than in the center. This Pu buildup causes a significant increase in the fission rate at the pellet periphery, relative to the fission rate in the bulk of the pellet. At elevated exposures, the result of this elevated fission rate is to produce a highly porous, fine grained structure. This altered structure region is called the **rim region.** The size of the rim region increases relatively progressively with increased exposure above ~40-45 GWd/MTU pellet average exposure. The primary considerations with the formation of the rim region are (1) possible increased fission gas release, (2) possible increased resistance to heat transfer, and (3) possible increased gaseous swelling under high rim temperature conditions. It is noted that the pellet rim may provide a cushion, or lubricating, effect that may reduce the consequences of pellet-cladding mechanical interaction.

Fuel restructuring and macrocracking. During the initial rise to power, the thermal stresses caused by the pellet radial temperature gradient cause the pellet to crack (primarily radially). With the release of strain energy, the cracked pellet segments relocate outwards toward the cladding (called fuel relocation or restructuring). With continued irradiation, additional outward movement of the pellet segments can occur. At ~mid-life exposures, the combined effects of pellet relocation, fuel irradiation swelling, and cladding creepdown result in a closed pellet-cladding gap. From this point, (1) a reduction in the fuel pellet expansion (such as caused by a power decrease) can result in partial gap opening, and (2) additional fuel expansion (by progressive fuel swelling or as a result of a power increase) can cause pellet radial cracks to (partially) close, thereby increasing the effective pellet stiffness, and imposing loading and deformation of the cladding. No particular change in this behavior is expected at elevated exposures.

Microcracking. During a rapid reactivity pulse where the pellet rim can experience significant heatup, and in the absence of significant constraint provided by the cladding, gas bubble expansion at the grain boundaries (most notably at the pellet rim) could lead to grain boundary cracking (decohesion). The result would be a release of fission gases to the fuel rod void volume with an increase in the fuel rod internal pressure and applied cladding pressure loading, with a subsequent reduction in the local pellet expansion. In the presence of significant cladding constraint, gas bubble expansion would be suppressed with a corresponding reactive increased loading of the cladding, likely with no significant fission gas release until release of the applied hydrostatic stress such as would occur on cooling. Additional pellet cracking can also occur on cooling, resulting in additional fission gas release, but correspondingly also reducing the gaseous swelling potential for the next heatup cycle.

Pellet-Cladding Interface. With the onset of pellet-cladding contact, a bond layer develops between the fuel pellet and the cladding. At elevated exposure, the magnitude (bond layer thickness) and extent (circumferential and axial surface coverage) increases. The development of this bond layer affects the ability of the pellet and cladding to move independently (effective friction), and thereby affects load transfer from the pellet to the cladding and the subsequent cladding stress state. The bond layer can fracture during cooldown or power reductions, leading to an intermediate state.

H.3. References

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